IMPACT OF OZONE EXPOSURE ON VEGETATION IN ONTARIO

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1.0 EXECUTIVE SUMMARY

This report presents the results of efforts undertaken in Ontario to assess the impact of existing levels of ozone and other oxidants on all types of terrestrial vegetation and to provide the basis for estimates of economic benefits from an ozone control program. Other objectives were to assess the response of vegetation to other regionally transported pollutants, to multiple pollutant exposures and to assess the adequacy of Ontario's existing 1 hour ozone criterion of 80 ppb, in terms of providing protection against adverse impacts on crops, ornamentals and forests in the province.

In the case of agricultural crops, the estimation of production losses was accomplished by a thorough review of the scientific literature as well as many unpublished government and university reports and conference proceedings and the development of a database for crop response to 7-hour seasonal mean ozone concentrations of 40 and 50 ppb. A total of 19 crops was assessed in this manner, and for 12 of the 19, a multi-component adjustment factor approach was utilized in the estimation of crop loss due to ozone exposure in Ontario to compensate for geographic, agronomic and experimental variability in the research results. Based on these findings and an analysis of the Ontario ozone database, it was subsequently determined by Donnan (1989) that agricultural field crop productivity in Ontario would increase by an average of $39 million with a range of $14 to $61 million per year with reductions in ozone to seasonal mean concentrations of less than 40 ppb. Statistical analysis of the ozone data from 1974-1988 revealed that this could be achieved by control efforts designed to meet the existing 1 hour ambient air criterion of 80 ppb.

In the case of ornamentals, including landscape trees, turfgrass and Christmas trees, productivity losses were more subjectively estimated at an average of 5% with a range of 2-7% in the southern portion of the province experiencing ozone seasonal means in the 40-60 ppb range. The economic impact of these losses has been estimated (Donnan, 1989) at $6 million with a range of $2 to $8 million per year, again based on ozone reductions to achieve the existing 1 hour ambient air criterion of 80 ppb.

Although foliar injuries have been documented on many forest species in Ontario, the state of knowledge at this time was insufficient to develop a reliable estimate of productivity losses. However, it has been noted in the report that in Ontario, the major portion of the

forest industry is located in an area of the province where ozone levels normally are lower than in the agricultural production areas of southern and central Ontario.

On the basis of this assessment, which formed the basis for estimates of productivity losses to crops and ornamentals which have a total economic benefit value of about $45 million and a range in benefits from approximately $17 to $70 million per year, it is concluded that control efforts should be directed towards the reduction of ozone levels in Ontario.

An evaluation of the impacts of other oxidants, including peroxyacetyl nitrate (PAN) and nitrogen dioxide failed to indicate any concern for direct impacts on vegetation at existing air quality levels. In the case of multiple exposures involving ozone and sulphur dioxide or acid rain/fog, there has been field type research that appears to rule out any significant enhancement of crop productivity losses. However, interactions involving some of these oxidants with ozone can not be ruled out due to a dearth of research conducted under growing season, field conditions. In the case of trees, the role of pollutant interactions which have been documented under controlled experimental conditions utilizing juvenile experimental material, has not been clarified for mature trees nor forest stands.

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TABLE OF CONTENTS

IMPACT OF OZONE EXPOSURE ON VEGETATION IN ONTARIO

1.0 INTRODUCTION

This document has been prepared as part of the Ontario's Oxidant Control Strategy (Lusis, 1989). The objective of the document was to assess the adverse impact of ozone exposure on terrestrial vegetation (crops, ornamentals, and forests) in Ontario and to provide the basis for the derivation of economic benefits which would result from an ozone control strategy. Associated objectives were to examine the potential response of vegetation to other regional pollutants, to multiple pollutant exposures and to assess the adequacy of Ontario's existing 1 hour ozone criterion of 80 ppb, in terms of providing protection against adverse impacts on crops, ornamentals and forests in the province. The concept of protecting plants from the impacts of ozone exposure also was examined and progress in this area summarized.

Because of the size of the literature database dealing with the impact of ozone on all aspects of plant response, this report did not attempt to deal in detail with the physiological, biochemical or anatomical aspects of plant response. Nor has it dealt with the many biological, environmental and climatic factors which regulate plant response to ozone exposure. All of these areas have been extensively reviewed in recent years (Guderian et al., 1985; Krupa and Manning, 1988). The report does, however, examine and discuss the many field oriented exposure:response indices that have evolved over the past few years and provides the rationale for the dose metrics which were chosen to characterize the impact of ozone exposure resulting under Ontario conditions. As part of this process, the results of an intensive ozone monitoring program in Ontario are summarized and presented in a format compatible with dose metrics utilized in the vegetation impact assessment.

A companion document (Donnan, 1989) has been prepared to explore the economic aspects of the oxidant control strategy for vegetation and other receptors which would benefit from a reduction in ozone concentrations. The vegetation based benefits from Donnan (1989) have been briefly summarized in this report.

2.0 OXIDANT EFFECTS ON VEGETATION

Photochemical oxidant air pollution was first recognized in 1944 when Middleton et al. (1950) observed toxic effects on vegetation in Los Angeles. Later, Richards et al. (1958), ascribed grape 'stipple' near San Bernardino, California to atmospheric ozone. Tobacco 'weather fleck' observed at Beltsville, Maryland in 1952,

and in southern Ontario in 1955 was attributed to ozone in 1959 (Heggestad and Middleton, 1959; MacDowall et al., 1963). Etiological studies to determine the relationship between atmospheric ozone and unexplained needle injuries on Eastern white pine trees were started in Canada in 1959 (Linzon, 1966) and in the U.S. in 1961 (Berry and Ripperton, 1963).

In 1960, another photochemical component of smog, peroxyacetyl nitrate (PAN), was identified as the cause of specific symptoms on Romaine lettuce and Swiss chard in California (Stephens et al., 1961). Studies on the adverse impact of one of the main precursors (also an oxidant), nitrogen dioxide, were reported in 1955 (Benedict and Breen) and later by Middleton et al. (1958). A brief review of these two regional oxidants, which also have the potential to adversely affect vegetation, has been provided to complete this assessment on oxidant effects. However, based on this information, impacts in Ontario from both PAN and nitrogen dioxide (or from other less phytotoxic nitrogen oxides) are of minor direct consequence. Their potential role in multiple exposures with ozone or as precursors of acidic precipitation and its interaction with ozone are discussed in greater detail in Section 2.3.2.

2.1 PAN

Peroxyacetyl nitrate (PAN) is the principal member of a family of nitrogenous compounds that can be photochemically produced in polluted atmospheres. These compounds are of concern because of their extreme phytotoxicity at concentrations in the low parts per billion range. Severe foliar injuries and economic losses of susceptible crops in southern California have been documented, while injury symptoms on indigenous plant foliage have been reported in the Netherlands and Japan (Temple and Taylor, 1983).

On the basis of published reports of ambient air monitoring (Temple and Taylor, 1983), including sites in Alberta and Ontario (Peake et al., 1988; Corkum et al., 1986), it is apparent that PAN concentrations in Eastern North America and other locations in Europe are lower by a factor of five to ten compared to those in southern California.

PAN injury has been observed in the field following concentrations of 15 ppb for 4 hours (susceptible ornamentals) and 25-30 ppb on leafy crops. Based on these dose:response values, the potential for serious PAN injury to plants in Ontario, where growing season concentrations average 1-2 ppb with occasional hourly peaks of up to 5-10 ppb, appears remote.

In an investigation of unusual injury to tomato plants in southwestern Ontario in 1972 (Pearson et al., 1974) characteristic PAN-type injury was observed. However, the investigation could not confirm the role of PAN, as no monitoring had been performed. These undersurface PAN-type symptoms on tomato (and later potato) crops were routinely observed throughout southwestern and central Ontario from that date on (Pearson, 1983). In 1978, Lewis and Brennan conducted controlled exposures on the varieties exhibiting symptoms in Ontario. They concluded that the injury was caused by a combination of ozone and sulphur dioxide and not by PAN. In a follow-up investigation in Ontario (Pearson, unpublished data), the symptoms which had been characterized as PAN-type (based on visual symptoms, phenological pattern of development and histology) were duplicated under controlled fumigation conditions with ozone. The appearance of these atypical ozone symptoms was related to ozone exposure during a very narrow range of leaf maturity. In the field, the undersurface symptoms also were experimentally investigated at Simcoe in 1980 (Pearson, unpublished data). Frequent observations of the plants provided a chronology of symptom development which was later compared to ozone, sulphur dioxide and PAN monitoring at the site. The symptoms occurred immediately following a time when maximum hourly ozone levels were in the 65-95 ppb range, sulphur dioxide was typically in the <10-20 ppb range (monitor malfunctioned just prior to the onset of symptoms) and PAN was less than 5 ppb. The antioxidant, EDU also provided complete protection to the foliage of treated plants. Based on these findings and the earlier controlled studies, it was concluded that the PAN-like symptoms observed on tomato crops in Ontario were in fact ozone induced. Accordingly, the appearance of these symptoms has, since that time, been ascribed to ozone exposure.

2.2 NITROGEN DIOXIDE

On the basis of the world literature which has recently been reviewed by Legge and Crowther (1987), nitrogen dioxide is the only nitrogen oxide that is considered potentially phytotoxic within the range of common ambient air concentrations. Under high light intensities, about 6000 ppb for 2 hours are required to injure sensitive plant species such as bean, tomato and cucumber (Taylor and MacLean, 1970). Low light intensity increases sensitivity of plants, with injury developing after exposure to 2500 to 3000 ppb for 2 hours.

Nitrogen dioxide can injure the same plants as ozone and at the same time within the leaf tissue. Injury symptoms are, however, generally different. Long term exposure to nitrogen dioxide (250 ppb) can cause reductions in growth and yield (Legge and Crowther, 1987); however, this observation is based on a limited amount of research.

Since ambient nitrogen oxide concentrations in Ontario or other parts of Canada rarely reach the short term injury threshold alone (Environment Ontario, 1988; Dann, 1989), recent research has focused on the effects of mixtures of two or more phytotoxic gases. Exposure mixtures involving nitrogen dioxide are discussed in greater detail in Section 2.3.2.

2.3 OZONE

Although ozone injury was first observed and documented under field conditions in the Los Angeles area, the majority of research which followed through the 1950's - 1970's was conducted with pot-grown plants under greenhouse or controlled environment conditions. The advantages of this approach were good reproducibility under specific pollutant exposure and climatic regimes, exhaustive evaluation of dose:response functions, and, in some cases, detailed examination of the physiological, biochemical and morphological behaviour of the pollutant.

Plant response to ozone is based on a sequence of biochemical and physiological events which culminate in some type of injury expression. The resulting cellular disturbances involve changes in both functional and structural characteristics, resulting from disruption of cellular membranes. These disturbances can result in foliar pathologies, altered carbohydrate allocation, reduced growth and yield as well as impacts on plant communities and ecosystems (Guderian et al., 1985).

As with many other pollutants, ozone effects on plant foliage can be categorized into acute, chronic and subtle effects. Acute symptoms are characterized by bifacial foliar lesions while chronic symptoms develop more generally from pigmented lesions, stippling, and bleaching to general foliar chlorosis. Subtle effects include reductions in plant productivity or vigour without visible symptoms.

Exhaustive lists of plant sensitivity/resistance to ozone under short term, controlled environment conditions have been published (Guderian et al., 1985; Heck et al., 1977). From a dose perspective, comprehensive reviews of the available literature were made by Jacobson (1977) and Linzon et al., (1975) and concentration:time profiles for acute foliar injury were developed for sensitive, intermediate and less sensitive species. Based on these and other findings, Guderian et al. (1985) developed a set of maximum acceptable ozone concentrations which, if met, would provide reasonable protection of vegetation from short term, acute exposures.

These thresholds are shown below:

Dose Thresholds[1] for Plant Response (Foliar Injury) to Ozone

Exposure Duration (hr.)	Sensitive	Resistance Level Intermediate (ppb)	Less Sensitive
0.5	150	250	500
1.0	75	180	250
2.0	60	130	200
4.0	50	100	180

[1] from Guderian et al., 1985

The importance of short term controlled environment ozone exposures and associated thresholds for foliar response has been overshadowed in recent years by the shift in research priorities to natural field exposure systems. The main reason for this shift was the growing body of evidence that indicated foliar injury was not an acceptable surrogate for ozone impacts on crop yield or tree growth. In many studies, significant reductions in yield or biomass growth were being detected in the absence of foliar symptom development, while in other cases, plants were able to sustain considerable foliar injury with no detectable loss in yield or productivity.

Any assessment of yield or quality parameters under field conditions is complicated by the ubiquity of ozone exposure, the effect of meteorological variables on ozone distribution within crop canopies and the effect of numerous biotic and abiotic factors which can alter plant response. Some of these difficulties have been partially overcome by progress which has been made in the refinement of field assessment techniques, including open-top chambers, open air fumigation systems and ambient air pollutant gradients (Ormrod et al., 1988).

The most comprehensive program which has emerged to address the issue of seasonal ozone impact on agricultural crop yield is the National Crop Loss Assessment Network (NCLAN) in the U.S. This seven year program was conducted from 1980-1986 at five geographic sites, chosen to represent distinctly different climatic conditions in regions growing different crop species. Open-top chambers were used to expose different agricultural crops to various regimes of ozone and sulphur dioxide, with plant yields being measured to determine dose:response correlations. The results of this program are described in numerous publications (Heck et al., 1982, 1983, 1984a, 1984b). A quality assurance program was also part of the

NCLAN study (Coffey et al., 1988).

In the most recent NCLAN assessment of yield losses, a three parameter Weibull model (Rawlings and Cure, 1985) was used to predict production losses of major crops in the U.S. from seasonal ozone mean concentrations of 40, 50 and 60 ppb. The results of these model predicted losses, which were based on NCLAN style field exposures for 11 crops, averaged 4.0, 7.6, and 10.1% for seasonal means of 40, 50 and 60 ppb, respectively (Heck et al., 1984a).

Although there was not a parallel program for forestry effects, numerous studies have been conducted in recent years using tree seedlings and open-top chambers similar to those used in the NCLAN program. The results of this research are discussed in Section 4.2.

2.3.1 Dose Metrics for Field Conditions

With the shift in crop research away from short term, controlled environment, foliar effect type studies towards long term, seasonal exposures under field conditions to assess impact on yield or productivity, a completely new set of decisions and assumptions was required in establishing exposure regimes and assessing dose:response. The NCLAN program was the first large scale study to address the issue of exposure under field conditions. Prior to NCLAN, only five field exposures of this type had been conducted (Heagle et al., 1988). Based on the earlier work of some of the NCLAN participants, a decision to utilize a 7-hour seasonal mean exposure statistic was made. Utilizing open-top chambers, ozone additions were made as a constant treatment relative to the hourly ozone concentration at each experimental site. Later, NCLAN adopted a proportional ozone addition based on predetermined factors above ambient concentrations. The 7-hour exposure also was increased to 12 hours per day.

Utilizing the findings from the NCLAN experiments and other similar studies, many retrospective attempts have been made to find a better exposure:response index or statistic that accurately characterizes crop response to ambient ozone exposure (Musselman et al., 1988; Lee et al., 1988, 1989; Laurence and Lang, 1988; Heagle et al., 1988; Hogsett et al., 1988; Rawlings et al., 1988; Cure et al., 1986; Lefohn and Runeckles, 1987; Lefohn et al., 1986, 1988; and Krupa and Kickert, 1987). It is beyond the scope of this document to thoroughly review this newly emerging and very contentious issue; however, a number of major findings have emerged that should be discussed, as they are relevant to the selection of an ozone control exposure threshold for productivity impacts.

It is apparent from a number of the general reviews of this area that no one exposure index or dose statistic is best for all crop species. The rigorous statistical search for relationships between crop response and a large number and variety of ozone averaging periods or exposure indices generally point to the importance of peak concentrations and weighted cumulative exposure indices. However, in many cases, these relationships can be very complex and difficult to interpret from a standard setting basis (Runeckles, 1988).

Indices based on peak or weighted cumulative concentrations (number of hours equal to or above a minimum concentration) also have limitations in that neither address the length of episodic events, intervals between episodes, the sensitivity of the target organism at the time of exposure or the amount of pollutant that enters the plant or canopy (Lefohn et al., 1988). Lee et al. (1988) examined a number of weighting systems in the analysis of some of the NCLAN data. They found that while no single index was best in relating ozone exposure to crop response, the indices that performed the best were those that cumulate the hourly concentrations over time, emphasize (weight) concentrations over 60 ppb and phenologically weight the exposure over the plant growth stage. In another evaluation of possible exposure indices, Musselman et al. (1988) evaluated a total of 163 ozone statistics using the NCLAN data set. Again, no one index was best for all crops, suggesting that conclusions from many of the single or double crop evaluations that had been performed by other investigators must be considered within these limitations. Lefohn and Runeckles (1987) reviewed some of the efforts which had been undertaken and attempted to relate these findings to the development of an ozone standard. They too concluded that the available evidence indicated that seasonal mean ozone concentrations do not accurately represent the exposure conditions which result in a particular plant response. In their analysis, the form of an ozone standard could be defined by exposure to a specific number of occurrences of the higher concentrations (multiple exposure standard). This could be expressed as "no more than X days per year on which the 1 hour average concentration of Y ppm ozone shall not be exceeded".

In response to the scientific debate which has emerged on the issue of exposure indices best suited to describe the biological response of plants to season long ozone exposures, the principals involved in the NCLAN program also examined some of their data to investigate the use of alternative dose statistics (Rawlings et al., 1988). Using three differential weightings of the hourly ozone concentrations (peak vs. non-peak, time of day of the exposure, and total hourly solar radiation) the authors concluded that the NCLAN dose statistic was a reasonable dose metric and that contrary to the findings of Lefohn, Lee and others, the effective dose metric is not well described by the weighting of the data for peak concentrations.

The performance of solar radiation as a weighting factor, representing a crude surrogate for crop phenology, suggested that the level of plant activity should be given greater weight or recognition in the development of dose indices.

Although there is currently no agreement as to the best index to represent plant response to ozone exposure, there appears to be growing evidence which indicates that the desirable index must adequately characterize all of the important exposure dynamic factors (concentration, duration, episode frequency, threshold) and that seasonal mean indices are not among the best.

In the absence of an acceptable and fully evaluated exposure index with which to assess the impact of ozone exposures on Ontario vegetation, a decision was made to proceed with an analysis of the North American crop response database from a seasonal mean perspective and to attempt to relate these findings to ozone exposures (seasonal means) in Ontario. Accordingly, contours of 7-hour seasonal means in Ontario were prepared and are presented in Figures 1-4. While it is recognized that the seasonal mean statistic is not the best predictor for vegetation impact, and therefore, not universally appropriate as an air quality standard, one of the reasons for its limitations was a lack of any relationship with peak hourly values (Lee et al., 1989), which are recognized as being important in vegetation response evaluations.

In deciding to utilize the seasonal mean statistic in the current vegetation impact analysis it was, therefore, important to determine if peak hourly ozone occurrences in Ontario were any better related to seasonal means than has been the case in the U.S.

Statistical correlations and regression were run on the rural only (117 site-years) and combined (rural+urban) data set (389 site-years) for the period from 1974-1988. The results of this analysis are presented in Figure 5 while predicted seasonal mean values from several 1 hour annual maxima are shown in Table 1. Although the equation (second degree polynomial) which best fits the expanded data set (1974-1988) has changed slightly from the earlier findings (linear) in the 1984 crop loss assessment (Linzon et al., 1984), the results still confirm that unlike the more vast and geographically diverse U.S. network, peak annual 1 hour maxima are reasonably well correlated with seasonal means in combined rural/urban locations in Ontario. This relationship is considerably weaker when only the rural data are considered. Based on this relationship, seasonal means at or below the generally reported lower limit for yield effects (<40 ppb) as indicated in many of the NCLAN publications, would be achieved in Ontario by the attainment of the existing 1 hour annual maximum ozone concentration of 80 ppb. Based on earlier acute exposure:foliar response data, the 80 ppb 1 hour level also will provide some degree of short-term foliar injury protection to

most of the sensitive species as described in the work of Guderian et al. (1985). It would not, however, provide complete short or long-term protection to a few very sensitive species or during periods of favourable climatic/sensitivity conditions.
Because of the change in the duration of ozone additions in the NCLAN studies from 7 to 12 hours of daily exposure, the Ontario data also were analyzed on a 12 hour basis. A comparison between the two averaging periods is shown in Table 2 and reveals very little difference in the seasonal mean concentrations between the two periods. The use of the longer daily averaging time does however, significantly increase the number of exceedances of hourly maxima (80, 100 and 120 ppb). Based on the NCLAN work, which revealed greater yield impact for 12 versus 7-hour exposures, it is apparent that the use in Ontario of the 7-hour statistic may slightly underestimate the impact of ozone on crop production.

Another criticism of the NCLAN experimental technique that has emerged relates to the use of a reference or control value of 25 to 30 ppb in solving the Weibull equations to predict crop loss. It is argued that these values are unreasonably low and therefore magnify the yield loss estimates.

While this seasonal mean may be unrealistic for many of the areas where the research was conducted, an evaluation of Ontario monitoring data confirms that in the more northern portions of the province not subject to the direct influence of contaminated transboundary flows or significant anthropogenic activity, 7-hour seasonal means of less that 25 ppb are recorded in excess of half the time, with over 80% of the values being at or below 30 ppb.
This criticism is, therefore, less valid under Ontario conditions than in areas of the US (or other parts of Canada) where much higher, naturally occurring ozone concentrations are prevalent.

In summation, although it is generally recognized that the seasonal mean ozone exposure statistic is not the best predictor for vegetation impact due to its inability to differentiate infinitely large numbers of ozone exposure profiles which could have very different impacts on vegetation, it was utilized in this assessment for several reasons:

1) there is currently no generally accepted alternative index which could be applied without extensive research/evaluation under Ontario exposure conditions

2) an analysis of the Ontario ozone database revealed that, unlike the situation in the U.S., and probably other areas of Canada where vast climatic and geographic differences exist, the relationship between peak hourly values and the 7-hour seasonal mean is reasonably well correlated; while this does not greatly improve the predictive power of the seasonal mean in terms of

plant response, it does indicate that under these more limited exposure conditions, there is a tendency for a somewhat more consistent pattern of peak exposures relative to average seasonal means.

3) for several of the crops evaluated, the impact of various seasonal mean ozone exposures was based on research conducted in Ontario; therefore, some of the problems of utilizing exposure:response data which were generated in the NCLAN study under hourly ozone profiles which may not have been characteristic of those producing similar seasonal means in Ontario, have, for some crops, been partially overcome. For those where no Ontario research was available, NCLAN or other similar studies were utilized and the loss estimates must, therefore, be considered as the best possible subject to the limitations discussed.

2.3.2 Interactions : Ozone and Other Air Pollutants

Because plant life in nature is rarely exposed to the influence of only one air pollutant, extensive efforts were initiated in the mid-1960's in which plants were subjected to combinations of ozone with sulphur dioxide, nitrogen dioxide and later, simulated acid rain or fog. The results of these multiple exposure experiments have been classified as additive (equal to the sum of the effects of the individual pollutants), synergistic (greater than the additive effects), or antagonistic (less than the additive effects). In 1966, Menser and Heggestad reported that tobacco plants suffered 25 to 38% leaf damage upon exposure to a combination of 240 ppb sulphur dioxide and 270 ppb ozone for 2 hours, whereas either pollutant alone at approximately the same concentrations and for the same time period caused no injury. The leaf injury caused by the combination of the two gases resembled typical ozone injury. Plants have been found to respond differently if the pollutant mixture regime is changed. For example, Tingey et al., (1973) found that injury on broccoli showed an additive response to a mixture of 250 ppb sulphur dioxide and 100 ppb ozone for 4 hour, whereas tobacco showed a synergistic response. However, if the regime was changed to 100 ppb sulphur dioxide and 100 ppb ozone for 4 hour, the reverse occurred, with broccoli showing a synergistic response, and tobacco an additive response. Heagle and Johnston (1979) demonstrated another factor that must be considered in assessing multiple exposure data. They found that when soybeans were exposed to mixtures of ozone and sulphur dioxide, the response to the mixture (synergism vs. antagonism) was dependent on the concentration used. Synergistic responses were associated with low level exposures, while antagonistic responses were documented at levels of exposure that

caused more severe injury. Other factors which have been shown to influence the response to multiple exposures include the duration and timing of the exposure and the age and condition of the plants (Mansfield and McCune, 1988).

As additional information concerning the complexity of the interpretation of multiple exposure data became apparent, research effort was aimed toward reducing the number of factorial components in the experimental technique. Ormrod et al., (1984) explored the concept of response surface techniques in studies with ozone and sulphur dioxide. Although this technique has not gained wide acceptance or use, it does offer many benefits and may be developed further as work in this area progresses.

In preliminary experiments, Heck (1968a) reported that a mixture of three pollutants (nitrogen dioxide, sulphur dioxide and ozone) each at a concentration of 50 ppb injured tobacco plants. Reinert and Gray (1981) reported that radish growth was a sensitive measure of the effects of the three pollutants in combination. Radish plants were exposed to either 200 or 400 ppb of the three pollutants alone or in combination for periods of either 3 or 6 hours. Nitrogen dioxide alone caused no visible injury, sulphur dioxide alone caused trace injury at 400 ppb for 6 hours, whereas ozone alone caused trace injury at 200 ppb for 6 hours. The exposure of radish plants to all three pollutants in combination caused greater than additive visible injury in comparison to the responses to individual pollutants or to any two-pollutant combination.

The foregoing results represent only a brief highlight of the literature which has been published on plant response to gaseous pollutant mixtures under short duration, high concentration dose regimes. Reinert (1984), Kohut (1985) and Mansfield and McCune (1988) present a more complete summary and discussion of work conducted in this area.

With increasing focus on acid rain and its precursors, and attempts to identify causal agents in a number of forest decline scenarios in the U.S., there has been increasing emphasis on interactions involving tree seedling response to ozone, acid rain/fog and sulphur and nitrogen oxides. As it is not possible to thoroughly review all such efforts, the reader is directed to some of the more recent studies in which these interactions were explored (Chappelka et al., 1988a, 1988b; Elliot et al., 1987; Reich et al., 1987, 1988; Stroo et al., 1988; Laurence et al., 1989; Chappelka and Chevone, 1986). As with the earlier crop research, the results of these and other multiple exposure studies have yielded a wide range of interactions between the exposure treatments, with ozone effects being exacerbated (synergism) in many of the experiments. However, in several studies, no adverse effects or interactions were apparent. Because these studies were conducted under controlled conditions

using seedling material, extrapolation or generalization to natural forest settings can not yet be made. Nevertheless, the work has focused attention on an important area, as in nature, single pollutant exposures do not occur throughout the life of a tree or forest stand. The importance of this concept is underscored by the search for causality in the many forest declines that are occurring throughout areas where ozone and other regional air pollutants (sulphur and nitrogen oxides and acidic precipitation) coexist at concentrations in the range of established threshold levels for the individual components. Clearly, until this uncertainty has been resolved, there can be no conclusive or quantitative statement regarding the magnitude of ozone impacts on forest systems.

In the area of crop yield effects, a better understanding of the impact of interactions of ozone with sulphur dioxide and acid rain/fog has emerged. In recent years a number of seasonal crop exposures under NCLAN type research conditions have been conducted (Takemoto et al., 1988; Kohut et al., 1987, 1988; Heggestad et al., 1986; Surano et al., 1987; Heagle et al., 1974, 1983; Temple et al., 1987; Kress et al., 1986; Reich and Amundson, 1984). In all cases, ozone in combination with sulphur dioxide and acid rain/fog at exposure levels similar to those encountered under field conditions remote from specific point sources have not resulted in enhanced yield loss above the additive individual pollutant effects. Although the field studies have not covered all crops for which ozone exposure information is available, the body of evidence appears to rule out significant interactive effects involving ozone and these major regional pollutants. Unfortunately, the interaction of ozone and nitrogen oxides or the three or four way interaction of ozone, sulphur dioxide, nitrogen oxide and acid rain has not been specifically addressed in any of the field oriented, crop yield response research.

2.3.3 Protection of Plants from Ozone Exposure

The concept of mitigating plant injury through cultural methods, protective chemicals and genetically tolerant varieties is not new and has been thoroughly reviewed (Heck, et al., 1977; Ormrod and Adedipe, 1974; Kender and Forsline, 1983). In the area of cultural management, it has been found that plant response to ozone can be slightly moderated by altering the mineral nutrition (nitrogen, potassium and sulphur) in the soil and by controlling the availability of water to the roots (Smucker and Saettler, 1978; Ormrod et al., 1973; Kender and Shaulis, 1976). However, unless the plants in question are being grown under controlled greenhouse conditions or in irrigated fields there is little or no possibility of utilizing these methods under normal agricultural field conditions. This also applies to other environmental factors

(light, temperature, relative humidity) which are known to condition the response of plants to ozone but which, in almost all cases, are beyond regulation under normal field conditions.

The use of protective chemicals has been explored in numerous studies since the first report in 1954 of reduced oxidant injury to pinto beans from the use of several fungicides (Kendrick et al., 1954). Since that time, the list of chemicals which have been used has increased (Kender and Forsline, 1983), but generally, protectants can be subdivided into two major groups - fungicides and antioxidants, and a third, smaller group consisting of growth regulators, vitamins, waxes, particulate and other chemicals. Of the two major groups, fungicides have received the most attention, with benomyl being the most widely studied because of its combined disease and oxidant protective properties and its suitability for use as a foliar spray or soil amendment (Heck et al., 1977). Other fungicides which have been examined include carbonin, zineb, maneb, thiram, ferbam, triarimol and dichlone. The effectiveness of some of these treatments with regard to protection against yield losses caused by ozone has varied from about 40 to 100% (Heck et al., 1977) depending on the crop, the ozone dose, as well as the frequency of application and other environmental parameters.
The list of antioxidants which have been evaluated is long and comprises simple reducing agents, commercial antioxidants, and specific antiozonants. The most promising chemical in this category was ethylene diurea (EDU) which was effective on many crop species either as a foliar spray or root application (Carnahan et al., 1978). However, because of problems associated with the economics of development and residue testing, EDU did not advance to the commercial market (Kender and Forsline, 1983).

In their summation of protective chemicals, Heck et al., (1977) outlined four major problems that have kept chemical protectants from practical use:

1. limited information on the frequency of application for effective protection and thus the cost of control.

2. uncertainty regarding the specificity of selected chemicals on different plants.

3. the lack of data on undesirable residues or side effects

4. the lack of predictive accuracy for high oxidant days for chemicals that are not persistent on the foliage or in the soil.

Problems in evaluating the effectiveness of the chemicals also have been encountered as crop growth improvement found in the laboratory or under controlled conditions is not always readily translated into protection to be expected in the field (Curtis et al., 1975). On the basis of the work which has been conducted, it is concluded that any significant advances in this area will result from the assessment of ozone and disease interactions and the selection and application of existing pesticide chemicals that possess fungicidal as well as antioxidant properties. This type of approach was undertaken for the potato crop in Ontario (Hofstra, 1981).

Other alternatives for the reduction of ozone impacts on crop plants are to develop genetic lines or strains that have ozone tolerance or to avoid planting sensitive cultivars in high ozone impact areas. Genetic manipulation and selection have not been actively pursued, although natural selection in most agricultural breeding programs probably has indirectly screened for those plants most tolerant to ozone. An example of this type of selection in a breeding program is evident in the tobacco research program at Delhi, Ontario, where ozone induced 'weather fleck' tolerance is assessed in the development and recommendation of new flue-cured cultivars (Pandeya et al., 1982). Progress also is being made in Ontario on the development of both an ozone tolerant and a high quality cultivar of white bean (Michaels, 1989).
The major problems in trying to avoid the use of sensitive crop varieties stem from a lack of current information on cultivar response to ozone as research has not kept pace with the rapid introduction of new cultivars. Another problem is that the information, when it is available, most often deals with seedling or young plant response (foliar injury) under selected and limited ozone exposures and in controlled plant growth chambers or greenhouses. Although there has been some attempt to relate these findings to mature crop, seasonal exposure response (Heck et al., 1988), these data usually have limited application in terms of crop yield potential under field conditions.

In summation, protection at the receptor level offers only limited potential in reducing the impact of ozone on the agricultural industry. In the case of forests, this possibility is even more remote. Moreover, as is pointed out by Lokey et al. (1979), these alternatives also involve certain costs which are associated with research, application and testing of chemical protectants, and changes in agricultural management procedures.

3.0 OZONE MONITORING IN ONTARIO

A network of oxidant monitors was established in Ontario in the early 1970's. In 1974, the first ozone specific, chemiluminescent

based monitors were introduced. During the following 15 years the network was continually upgraded, with the addition of stations in many rural areas and in additional urban areas due to the inclusion of ozone in Ontario's new Air Quality Index. In 1988, there were valid data for 47 monitoring stations, with about one third of those in rural areas or small rural towns.

The results of the annual ozone monitoring are published each year by the MOE. Trends in these data and the associated episode analyses have been recently presented by Kurtz et al. (1989). However, in terms of plant response, these summaries are of limited value, as they focus on hourly maxima and annual means.

As was discussed in Section 2.3.1, the Ontario ozone database (1974-1988) has been re-analyzed, using the 7-hour seasonal mean statistic. Table 3 presents a summary of ozone concentrations at five selected rural and urban locations, representative of most areas of the province. In all cases except for Dorset, the monitoring stations selected for summary analysis had at least 10 years of continuous data. Results for Dorset were included in this table because of intensive forest research underway at that site in recent years.

In this table, the arithmetic average (1974-88) hourly maxima (based on 24 hour monitoring from Jan. - Dec.), 7-hour seasonal means and number of hours ozone exceeded levels of 80, 100 and 120 ppb are contrasted with the corresponding results for 1988. Using these data (9 sites) and results from an additional 20 sites in Ontario where ozone monitoring had been performed for a minimum of 8 years (29 sites total), the average (1974-88) 7-hour seasonal means were computer contoured using the kriging technique (Surfer 3.00, 1987). The use of kriging as a method of spatial interpolation for estimating air quality has been utilized in the NCLAN assessment of ozone distribution in the U.S. It offers several advantages but also has limitations which must be considered before use (Knudsen and Lefohn, 1988). Based on the assumptions and limitations, it was concluded that contouring of the seasonal means for sites in Ontario would be adequately described via this technique. The ozone database was also examined to establish contours of maximum and minimum seasonal means. This was conducted by determining the two years of monitoring results which were either the highest or second highest (similarly for lowest) across the province. A third value, representing the next highest (any year) value at each monitoring site was used in the averaging process. In the derivation of the maximum seasonal mean, the two years selected for all sites were 1988 and 1983. For the minimum contours, the data for 1982 and 1986 were used. The contours of 7-hour average, maximum and minimum seasonal means are presented in Figures 1 - 3 . For comparison purposes, the 1988 seasonal mean contours also are presented in Figure 4. In each figure, the contours for seasonal means of 40

(36-45) and 50 (46-55) ppb ozone are identified as Regions 4 and 5, respectively. In 1988, an additional Region 6 was necessary to contour the much higher seasonal mean of 60 (56-65) ppb, that was experienced along the north shore of Lake Erie.

Table 4 has been prepared from the Canadian NAPS database, and provides a comparative basis for trends in ozone levels in Eastern Canada. It is apparent from this table that ozone levels in southern Ontario are significantly higher than at most sites to the east. This conclusion is also apparent from another recent review of ozone levels across Canada (Dann, 1989).

To provide some indication as to annual trends in seasonal mean ozone concentrations, Table 5 was prepared using the same selected rural and urban sites as in Table 3. Data from two of these sites (Centralia and Stouffville) have also been graphed in Figure 6. From this presentation it is apparent that there has been no significant trend in the severity of ozone contamination in Ontario over the last 15 years. There was some indication that levels were decreasing from 1984 to 1986; however, this gradual decrease was reversed in 1987 and in 1988 some of the highest levels ever were recorded, particularly at sites in the southwestern portion of the province.

4.0 OZONE EFFECTS ON VEGETATION IN ONTARIO

In Ontario, the first indication of transboundary ozone movement across Lake Erie was documented (Mukammal, 1960) following extensive work on the relationship between the incidence of weather fleck on tobacco and meteorological conditions associated with the build-up of ozone. Since 1960, a number of large-scale meteorological investigations (Anlauf et al., 1975; Yap and Chung, 1977; Yap et al., 1988) have confirmed these early findings and shown that high ozone levels generally are associated with regional southerly/southwesterly air flows associated with back or centre of the high pressure situations. These investigations have indicated an overall ozone contribution from the U.S. of about 50-60% during the summer months with an even greater contribution during episode periods. Contributing to these influx patterns are relatively minor, localized downwind urban effects which can add to the already elevated background levels.

4.1 Agricultural Crops

In an effort to estimate the severity of crop yield loss in those portions of Ontario subjected to potentially injurious summer ozone concentrations, a thorough review was undertaken for all major crop species grown in Ontario. The literature review consisted of

published research reports, unpublished documents and internal reports from government agencies and universities dealing with productivity losses under field conditions in North America. The results of this review for the 12 most frequently assessed ozone sensitive crops are displayed in Table 6.

In all cases, the review of the literature focused on experimental findings in which crops were exposed to seasonal ozone concentrations in a range typical of those encountered in Ontario. These included seasonal means of 40 and 50 ppb. Crop loss data for exposures greater than these two values were included only if the publication included yield models (Weibull, Quadratic or Linear) which were subsequently solved to generate average yield loss for these two seasonal mean ozone concentrations.

The literature review also was limited to research in which crop productivity was assessed under field conditions utilizing open-top field chambers, air exclusion systems, air plenum systems, closed-top field chambers or chemical protectants. In many of these experiments the impact of additional factors, such as soil water stress, disease control or mixtures of ozone with other air pollutants also was assessed.

In the previous Ontario assessment (Linzon et al., 1984), the average yield loss values for each crop were derived based primarily on the experience and professional judgement of the authors. This technique involved the approximation of an average yield loss value, taking into consideration the amount of experimental evidence, the diversity of published cultivar response information, the geographic proximity of the research findings to Ontario and any other factors which were judged to be of significance in terms of equating the findings to Ontario conditions. The average crop loss values were then assigned an arbitrary +/- 50% variation to account for crop response under different climatic and edaphic conditions.

To overcome some of the weaknesses of this subjective and non-reproducible approach, the 1989 assessment has been modified to incorporate a mathematical adjustment factor approach based on defined assumptions. The 1989 estimates also utilize variability in seasonal ozone exposure severity to delineate the spatial extent of seasonal ozone impacts.

4.1.1 Crop Loss Adjustment Factor

As a means of eliminating the use of estimated ranges of yield loss values for crops in ozone Regions 4 and 5 (Linzon et al., 1984) and to avoid the limited and selective use of specific research results to arrive at regional crop loss values as was the case with the estimates from the NCLAN work (Heck et al., 1984a, 1984b; Adams et

al., 1985, 1988; the California estimates (Howitt et al., 1984; Olszyk et al., 1988a), the Tennessee estimates (Brewer et al., 1988) and the Minnesota estimates (Benson et al., 1982), a more consistent adjustment factor approach was developed which would permit the use of all available ozone response data for each crop.

The mathematical derivation of the adjustment factor is detailed in Figure 7. As described, the adjustment of the average yield values for seasonal means of 40 and 50 ppb (actual reported yield loss values or model derived calculations) has been predicated on arbitrary assumptions in three areas. These factors include: geographic variability, agronomic variability and experimental variability.

Within the agronomic and experimental factors, the variation has been further partitioned into sub-components. A description of the components of the three factors is shown below:

VARIABILITY FACTOR	**SUB-COMPONENT**	**WEIGHT**
geographic	location of research	100
agronomic	cultivars evaluated	100
	soil moisture conditions	100
experimental	total valid data	300
	total modelled data	100
	total statistically significant data	300
TOTAL		**1000**

4.1.1.1 Geographic Variability

The geographic location of the reported research was assigned a total of 100 (10% of total). The research results were partitioned into three broad geographic areas:

Ontario and NE-U.S. States
SE, Mid-W and W-U.S. States
SW-U.S. States

The individual states comprising the various regional categories are shown in Table 7. In order to assign as much weight as possible to

the available research conducted in Ontario and neighbouring NE U.S. states, this group was assigned a Regional Weight Factor (RWF) of 100. Corresponding RWF's for the other more remote (to Ontario) experimental locations were set at 50 and 10 for SE/M-W/W and SW, respectively.

4.1.1.2 Agronomic Variability

4.1.1.2.1 Cultivars Evaluated

Considering the variability in cultivar response which has been demonstrated in numerous research findings, a factor of 100 (10% of total) was assigned to reflect the extensiveness of the cultivar testing performed on a given crop. As shown in Figure 7, the full score was based on crop loss evaluations for at least 20 different cultivars.

4.1.1.2.2 Soil Moisture Conditions

In the majority of controlled exposures in which crops have been assessed for response to ozone under different soil moisture regimes (Table 6), the results have confirmed a significant enhancement of crop response under irrigated conditions. These results agree with the findings from most earlier work (Guderian et al., 1985; Heck, 1968a), which indicated that plants suffer greater foliar damage when exposed to ozone under optimum soil water conditions.

Accordingly, a factor of 100 (10% of total) was assigned to reflect the conditions under which the various experiments had been performed, with sub-factors of 100 and 1 being assigned to those studies in which the plants were grown without irrigation or under well watered conditions, respectively. In effect, this represents an approximate weighting of 10% for soil moisture conditions.

4.1.1.3 Experimental Variability

4.1.1.3.1 Total Valid Data

As a measure of confidence in the experimental findings for a particular crop, the size of the available data set was assigned a weight factor of 300 (30% of total). The maximum number of valid results for a full factor weight (300) was set at 120 yield loss data points.

4.1.1.3.2 Modelled Data

In order to give greater weight to the NCLAN style studies in which several seasonal ozone doses were administered, either as constant or proportional amounts above ambient background levels, and yield

response models (Weibull/Linear/Quadratic) were developed, an adjustment factor of 100 (10% of total) was assigned. As shown in Figure 7, this factor was based on the percentage of the total data set.

4.1.1.3.3 Statistically Significant Data

In many of the experimental yield response studies, the results were not statistically significant (compared to background seasonal means of 25-30 ppb). To adjust the average crop loss values which were based only on those significant at the 95% level of probability, an adjustment factor of 300 (30% of total) was assigned. As shown in Figure 6, this factor was based on the percentage of the total data set.

In the case of all crops, a computer spreadsheet was set up to calculate the adjustment factors. This system also will permit consistent revision of these factors as new research is conducted. The calculated adjustment factors for the 12 crops ranged from 0.33 to 0.61. The details of the adjustment factor calculations with the corresponding un-adjusted and adjusted crop loss values are shown in Table 7. A separate summary of the adjusted crop loss values for the 12 sensitive "At Risk" crops and additional group loss estimates of 1 and 2% for seven additional "Marginally At Risk" crops for which more limited experimental data have been developed, are shown in Table 8. These yield loss estimates for the 19 crops formed the basis of the subsequent calculation of the monetary nature of the benefits to be derived from reducing ozone concentrations in Ontario (Donnan, 1989).

The 1989 benefit calculations also incorporated variability in seasonal ozone exposure to give a range of potential benefits, based on average, minimum and maximum ozone seasonal means over the period from 1974-1988. The derivation of these zones is described in Section 3.0.

4.1.2 Crops at Risk

As a supplement to the crop loss summary which is presented in Table 6, the following information provides a general overview of the impact of ozone on the 12 major "At Risk" crops. A more general discussion of the seven additional "Marginally At Risk" crops for which insufficient evidence was available to utilize the adjustment factor approach, also is presented.

4.1.2.1 White bean

In 1961, bronzing and rusting of white bean foliage was reported (Clark and Wensley, 1961) throughout southwestern Ontario and the

resultant defoliation was estimated to have resulted in a loss of approximately 600 pounds of beans per acre (45% yield loss) in severely affected fields. Following extensive field work in 1965 and 1967, the disorder was found to be associated with the occurrence of elevated levels of atmospheric ozone (Weaver and Jackson, 1968). The symptoms, which first appear sometime between flowering and normal plant senescence, a critical period in the development of yield potential, appear as a bronze-coloured necrotic stipple on the foliage which, as it becomes more severe, results in premature leaf drop and reduced seed set.

In an effort to assess and compare the annual severity of ozone injury on sensitive white bean plants, Ministry of Environment (MOE) staff have conducted visual assessment surveys throughout the major production areas in southern and southwestern Ontario since 1971 (Table 9). In the 16 years of study over 690 visual ratings of farm fields or experimental cultivar plantings have been made with injury severity ranging from minimal amounts to severe bronzing and associated premature foliar loss (Pearson, 1983). These annual visual surveys also ruled out any significant cultivar resistance and confirmed that in any year the bronzing symptoms could appear throughout all bean production areas, with no particular pattern being apparent.

Experiments utilizing chemical protectants against ozone injury have helped to provide information on yield losses related to the bronzing disorder in Ontario. In 1973, a 13% yield increase was associated with the reduction in bronzing severity (Curtis et al., 1975), while in 1976, yield increases of up to 36% (27% yield reduction) were realized (Hofstra et al., 1978).

In 1977 and 1978 white bean yield increases with antioxidant chemical protection were not as high (Toivonen et al., 1982) due to climatic extremes (drought). The overall response in these years was a 16 and 4% increase in yield, respectively. Individual cultivar response at the different locations and for different seasonal 7-hour mean ozone concentrations is shown in Table 6. In other extensive chemical protectant studies during 1977, 1978 and 1979 (Temple and Bisessar, 1979; Hucl and Beversdorf, 1982; Toivonen, 1980) numerous varieties were examined across most of southwestern Ontario (Table 6).

In a later study in Ithaca, N.Y. conducted as part of NCLAN, Kohut and Laurence (1983) demonstrated significant yield reductions with red kidney bean. In this case, the exposures were limited to a 21 day period during pod filling using constant ozone additions for 7-hour per day. Weibull predicted yield losses for seasonal means of 40 and 50 ppb are shown in Table 6.

On the basis of the foregoing research results (Table 6) and the

adjustment of these data as described in Table 7, the estimated yield losses for Regions 4 and 5 are 10.6 and 10.7%, respectively (Table 8). These findings are in good agreement with those of Adomait et al. (1987) who examined the loss from another perspective utilizing an economic model.

4.1.2.2 Potatoes

The foliar symptoms referred to as "speckle leaf" on this crop usually appear after mid-July when the plant has flowered and the tubers are developing. As the demands for photosynthetically produced nutrition at this time are at their peak, the potential for adverse yield effects is considerable. The symptoms appear either as a blackened stipple or flecking on the upper leaf surface which can coalesce and become bifacial necrotic lesions; or as undersurface, irregularly sized, silver-grey lesions which also can become bifacial as they increase in size and severity. Adding to the total impact of this injury are findings (Bisessar, 1982; and Holley et al., 1985) which demonstrate that ozone injury predisposes the plants to attack by the early blight disease organism, thereby necessitating additional disease control treatments.

In Ontario, ozone induced foliar symptoms were observed as early as 1954 (Johnson, 1972) and in later years (McKeen et al., 1973). On the basis of yield assessment studies conducted in Ontario and in the NE USA, yield losses and tuber quality effects have been documented on several of the most sensitive processing cultivars. MOE staff also have conducted annual foliar injury assessment surveys throughout the major potato production areas in Ontario since 1977 (Table 9) and in that time have examined over 550 plantings and recorded foliar injury development ranging from less than 1 to 30% leaf area (Pearson, 1983).

In studies using antioxidant protective chemicals, potato yield losses in Ontario with and without disease control were 24.2% and 26.2% respectively, for Norchip at a seasonal mean of 42 ppb (Bisessar, 1982). An average (significant) yield loss, of 8.2% in an ozone sensitive cultivar (Norchip) also was reported during a three year trial in Ontario (Holley et al., 1985). This loss could be attributed to ozone effects which were apparent under a disease control program when the 7-hour seasonal mean was just below 40 ppb; no demonstrated yield effects were detected with two other more ozone resistant cultivars (Chieftan and Kennebec) in the same three year Ontario trail (Holley et al., 1985). The Ontario trials using chemical protectants compare favourably with a more complex NCLAN stye investigation which was performed in 1986 (Pell et al., 1988). This study (Table 6) also demonstrated significant tuber quality effects. Another NCLAN style study was conducted earlier (Foster et al., 1983) in California; however, because of the use of a different

dose statistic (ppm.hr), the results could not be included in Table 6. The findings from that study did however, confirm a linear dose-response to season long ozone exposures in terms of tuber number and total tuber yield.

In an earlier Ontario study (Hofstra et al., 1983) using EDU, variable degrees of yield loss were reported for several commercial cultivars at four locations. At Simcoe, yield loss ranged from N.S.-22.1% and N.S.- 27.8% in 1977 and 1978, respectively. These losses correspond with a seasonal 7-hour ozone mean of 55 ppb in both years. At Cambridge, no significant yield losses were detected in 1977 or 1978. On the basis of the limited foliar injury protection in this study at these locations as well as at Ridgetown and Alliston, it was concluded that the use of EDU was not fully accounting for yield loss associated with ozone exposure. Although ozone dose metrics were not comparable, Clark et al., (1983) reported yield losses to two potato cultivars (via. EDU) in New Jersey ranging from 18.8-30.9% in 1980 and 25.4% in 1978.

On the basis of the foregoing studies as well as general reports of foliar injury and/or yield losses in the NE and SW USA (Mosley et al., 1978; Hooker et al., 1973; Foster et al., 1983) and a documented 50% loss to a sensitive variety under greenhouse conditions (Heggestad, 1973) there is strong evidence that this crop is reduced in potential yield by ozone exposure under Ontario conditions. From the data in Table 6, and the adjustment of these data as shown in Table 7, the estimated yield loss for Regions 4 and 5 are 5.6 and 6.9%, respectively (Table 8). Other factors which have not been included are possible adverse effects on tuber quality (Pell et al., 1980, 1988), the increased costs associated with additional disease control, and the fact that at least one agronomically important cultivar (Norland) can no longer be commercially grown due to extreme sensitivity to ozone.

4.1.2.3 Flue-cured Tobacco

'Weather fleck' of tobacco, so named because of its relationship to certain weather conditions, has been recognized as an ozone induced foliar disorder in Ontario since 1954 (Cole and Katz, 1966).

The symptoms appear on newly expanded leaves, the younger and older leaves of tobacco being more resistant. They start on the upper leaf surface as greyish, water soaked lesions which become light ivory to tan-brown in colour with time. In more severe episodes the lesions can coalesce into larger flecks or spots and become bifacial with increasing severity. Successive episodes of ozone fumigation result in new lesions appearing on healthy tissues of recently injured leaves as well as newly expanded leaves higher on the main stem.

Although considerable success has been achieved in Ontario, in the area of breeding resistance into commercially acceptable tobacco cultivars, yield losses associated with this crop continue to affect tobacco production (Ormrod et al., 1980; Watson and Sheidow, 1982).

In 1972 and 1973, decreased leaf weight and quality (0.73%) were estimated by Gayed and Watson, (1975), while estimates of tobacco crop loss for the years from 1975-1981 have varied from 0.2-2.5% (Watson and Sheidow, 1982). A visual assessment of foliar injury severity consisting of 33 separate observations throughout the major tobacco production areas of southern Ontario in 1977 by MOE staff confirmed the presence of foliar injury development ranging from less than 1 to 20% on flue-cured tobacco species (Pearson, 1983). These and other Ontario data were not included in Table 6 because they were not site specific and therefore could not be equated with a corresponding seasonal mean ozone concentration. However, in the North Carolina study by Heagle et al., (1987a) significant yield losses were demonstrated with 7-hour seasonal means regardless of whether the ozone additions to the background levels were constant or proportional. Average tobacco yield (all treatment levels) was, however, 10% less for plots receiving proportional ozone additions for 12 hour per day (1000 - 2000 EDT) than for corresponding proportional 7-hour (1000 - 17000 EDT) ozone means.

Based on the NCLAN research and supported by visual estimates in Ontario, loss of tobacco production has been estimated (Tables 6-8) at 2.1 and 3.9% for Regions 4 and 5, respectively.

4.1.2.4 Tomato

Tomato is an ozone sensitive crop species and has been investigated for cultivar sensitivity (based on foliar injury) by a number of researchers. Typical injury symptoms are frequently reported in the field in Ontario (Pearson, 1983).

There are numerous reports which document the adverse effect on tomato yield due to ambient (MacLean and Schneider, 1976; Oshima et al., 1977, Heggestad et al., 1986 Heck et al., 1984b) or controlled environment exposure (Henderson and Reinert, 1979).

In North Carolina (Henderson and Reinert, 1979), early marketable yield of some tomato cultivars was significantly reduced by exposure of the plants to ozone prior to their establishment in the field. In spite of the fact that the final total yield was not affected, an economic loss was predicted based on the price differential between the early and late season markets. In the New York study, MacLean and Schneider (1976) documented a 33.7% yield reduction effect for plants grown in unfiltered chambers relative to charcoal filtered

chambers. The calculated average 7-hour seasonal mean in the filtered chamber over the duration of this experiment was 22 ppb ozone while that in the unfiltered chamber was 63 ppb.

As part of the NCLAN study, yield loss with Murrieta tomato in California (Surano et al., 1987) was estimated at 2.4 and 7.5% for seasonal 7-hour exposures of 40 ppb in 1981 and 1982, respectively and 4.9 and 14.4% at 50 ppb in 1981 and 1982, respectively. Heggestad et al., (1986) reported a 16.3% yield loss for Jet Star using filtered versus unfiltered open-top field chambers in Beltsville with a calculated 7-hour seasonal mean of 50 ppb compared to 15 ppb in filtered chambers.

In Ontario there are two reports citing an adverse effect of ozone on tomato yield. In one (Legassicke and Ormrod, 1981) a yield reduction of 23.7% was recorded for one cultivar compared to tomato plants afforded chemical protection. In the other study, Ormrod (1983) found reductions in tomato yield for several cultivars at several locations in both 1980 and 1981. Although many of the cultivar comparisons were not statistically significant, there were some that approached 30% yield reduction.

On the basis of these yield loss findings, the annual presence of early and mid-season visible foliar symptoms in Ontario and the documented wide range in cultivar response, adjusted annual yield losses for all fresh and processing tomato crops in Ontario have been estimated at 1.6 and 5.4% for Regions 4 and 5, respectively (Table 8).

4.1.2.5 Onion

Onion leaf dieback and flecking have been attributed to a number of parasitic and non-parasitic agents since the first report of the disorder in Wisconsin in 1903 (Whetzel, 1904). Subsequently, the search for the causal agent in the tip-burn or blast syndrome centred on atmospheric ozone. Engle et al., (1965) found a close relationship existed between the presence of flecking and tip-burn in onions and high levels of ozone. Engle and Gabelman (1966) later published on the genetic resistance of certain cultivars of onions to ozone exposure.

In Ontario, Wukasch and Hofstra (1977a, 1977b) examined the effects of ozone exclusion and chemical protection on the yields of field grown onions. They documented a 28% yield reduction in non-filtered compared to charcoal filtered chambers, and a 22% yield reduction in control plants (Autumn Spice) compared to those provided with an antiozonant protectant. Another cultivar (Rocket) failed to confirm these significant protectant effects.

In a later California study, using closed-top field fumigation chambers, McCool et al., (1987) demonstrated a significant yield loss for green bunching onions exposed to various 12 hour seasonal mean ozone concentrations. The linear response model predicted yield losses of 14.9% and 24.8% using the 12 hour seasonal mean statistic.

Although field exposure research has not been as extensive with this crop compared to several others, there is sufficient information to calculate yield loss under Ontario conditions (Table 6). Based on these data, the adjusted yield losses for Regions 4 and 5 are 5.6 and 9.2%, respectively (Table 8).

4.1.2.6 Winter wheat

Until recently, little was known concerning the impact of seasonal ozone exposure on the yield of winter wheat. The work of Shannon and Mulchi (1974) and Sechler and Davis (1964) had indicated that wheat was sensitive to short term acute exposures at anthesis under controlled environment and greenhouse conditions and that, to a limited extent, cultivar differences were apparent.

In 1978 and 1979, Mulchi et al., (1986) conducted field experiments in Maryland utilizing open-top chambers and 6 cultivars of soft red winter wheat. Although the ozone doses were not expressed in the NCLAN format, all six cultivars exhibited susceptibility to ozone injury during anthesis. In an earlier field experiment (Phillips and Runeckles, 1974), wheat biomass was reduced with exposure to five hour per day at concentrations ranging from 80 to 100 ppb. Yields were not reported.

In later NCLAN studies (Kress et al., 1985; Kohut et al., 1987), utilizing both constant and proportional ozone exposures, significant yield losses were recorded for both soft and hard winter wheat cultivars. These and other controlled field study results are shown in Table 6. In the latter study, ozone was shown to accelerate senescence of flag leaves and heads, with reductions in yield being highly correlated with reductions in net photosynthesis (Amundson et al., 1987). Based on these data, the adjusted yield losses for Regions 4 and 5 are 3.4 and 5.5%, respectively (Table 8).

4.1.2.7 Soybean

In the early 1970's, a number of greenhouse studies were conducted which documented the foliar response of a number of soybean cultivars to acute and chronic doses of ozone (Heagle, 1979; Howell and Kremer, 1972; Tingey et al., 1972). It was later demonstrated (Heagle and Letchworth, 1982) that neither foliar injury nor the vegetative shoot weight response of cultivars to ozone allowed

reasonable prediction of cultivar yield response. In the late 1970's a number of studies confirmed crop yield losses under field conditions in studies utilizing open-top field chambers equipped with ozone filtration devices (Heagle and Heck, 1980; Kohut et al., 1977). These studies underscored the need for more accurate assessments of yield effects utilizing open-top chambers with supplemental ozone additions (Kress and Miller, 1983). During this period of active NCLAN supported and independent research, a number of investigations utilizing a number of potentially interactive variables were conducted. These included interaction with sulphur dioxide, acid rain and soil moisture. The results of these investigations, where actual seasonal means were in the range of those encountered in Ontario or where Weibull or other response models could be solved for seasonal means of 40 - 50 ppb, are shown in Table 6.

With the exception of the chemical protectant studies (Smith et al., 1987; Brennan et al., 1987) and an earlier open-top chamber study (Howell et al., 1979), the experimental yield losses from the various controlled exposure studies (Kohut et al., 1986, Reich and Amundson, 1984; Heagle et al., 1986, 1987b) revealed a highly uniform degree of plant response, considering the potential influences of location, exposure metrics, cultivar, soil moisture and other environmental variables.

Because of this crop's sensitivity to ozone and its importance to U.S. agriculture, soybean has been the primary focus in the experimental study of ozone:soil moisture interactions and the development of predictive moisture stress models for crop loss assessment (Heggestad et al., 1985, 1988; Heagle et al., 1987; King et al., 1988; King and Nelson, 1987). On the basis of this work, King and Nelson (1987) predicted a 23% decline in sensitivity to ozone based on a 1980 U.S. ozone exposure scenario. For the period from 1979-1983, the mean predicted ozone impact on soybean yield was reduced 19% by moisture stress.

Based on these results and others as presented in Table 6, there is a high degree of certainty that ozone exposure of this crop in Ontario is resulting in significant yield loss. The adjusted loss estimates for Regions 4 and 5 are 3.2 and 6.2%, respectively (Table 8).

4.1.2.8 Sweet corn

In the first report ever to demonstrate yield loss in an agronomic crop exposed to long-term, low levels of ozone under field conditions using field exposure chambers, Heagle et al., (1972) evaluated the response of two cultivars of sweet corn. Ozone injury was described as small white or tan adaxial necrotic spots plus

early chlorosis and senescence on the lower leaves. Growth reductions were not proportional to injury severity. The reductions in ear fresh weight are shown in Table 6.

In California, Thompson et al., (1976) used open-top field chambers with and without carbon filtration and demonstrated foliar symptoms which were similar to those reported in other studies. Both cultivars (Monarch Advance and Bonanza) were seriously injured in ambient air; however, growth and yield parameters were more significant for Monarch Advance, with the greatest response being an effect on number and quality of seeds set on primary ears. Although Thompson et al., (1976) did not equate the yield reductions to seasonal ozone concentrations, this was done in a subsequent publication by Olszyk et al., (1988a). These data are shown in Table 6.

As was the case with onion and flue-cured tobacco, the amount of field research on this crop is less extensive than for several other crops. However, based on the published work and on chemical protectant work which was performed in Ontario, adjusted estimates of yield loss for Regions 4 and 5 (1.4 and 2.3%, respectively) have been developed (Table 8).

4.1.2.9 Green Snap Bean

Both acute and chronic ozone exposures of horticultural snap, lima, bush or common beans have been shown to cause foliar injury (Blum and Heck, 1980; Meredith et al., 1986). Large numbers of studies conducted under different environmental conditions, using different ozone concentrations and exposure durations also have demonstrated the susceptibility of snap beans to ozone effects on dry matter accumulation, relative growth rate, pod production, nodulation and leaf nitrogen content. These studies are summarized in Blum and Heck (1980).

Studies of yield effects under field conditions using open-top chambers also have been conducted, although in many cases specific data on exposure parameters were not provided. In a 5 year study in Maryland (1972-1979) average yield reductions for snap beans ranged from 5-27% (Heggestad, 1980). Monitoring results for a nearby site (Beltsville) were provided by Heggestad et al., (1980) and revealed that during the period from June through August, hourly ozone values equalled or exceeded 100 ppb an average of 14 times per year. This frequency is similar to many sites in southern Ontario (Table 3).

In 1973, MacLean and Schneider (1976) detected a 26% yield loss for snap beans in unfiltered open-top chambers compared to similar plants grown in carbon filtered air. The average daily (0600-2100 EST) ozone concentration in the unfiltered chamber over the 43 day

duration of the experiment was 41 ppb and, although not reported, the 7-hour seasonal mean was estimated (from a graph of hourly concentrations) to be approximately 60 ppb.

The most comprehensive and relevant field evaluation of ozone impact on common bean cultivars has recently been reported by Heck et al., (1988). The results of this two-season evaluation using four different cultivars in Raleigh, N.C. are shown in Table 6. In addition to the yield loss information, the authors concluded that the results provided strong support for the concept of predicting yield reduction under chronic ozone exposure based on foliar screening results and that the NCLAN concept of comparing relative yield losses may permit comparisons of results across seasons, years and cultivars, even though actual yields may vary greatly.

From all available experimental evidence (Table 6), adjusted yield losses for all cultivars of green snap bean have been calculated at 2.2 and 4.4% for Regions 4 and 5, respectively (Table 8).

4.1.2.10 Spinach

Several studies have been published documenting the impact of ozone on spinach plantings (Daines et al., 1960; Manning et al., 1972) and confirming cultivar response variability and typical short term acute foliar symptoms. In 1976 (Heagle et al., 1979a) conducted the first growing season exposures to determine whether spinach cultivars vary in sensitivity and to determine threshold doses of ozone for injury and decreased shoot weight.

The results of this study, using Weibull models from a subsequent publication by Heck et al., (1983) are shown in Table 6.

The authors confirmed that under seasonal exposure regimes, the foliar symptoms resembled those described for acute exposures; however, the major symptom was chlorosis, as opposed to bifacial necrosis. There were no relationships between foliar injury and shoot fresh or dry weight.

Adjusted yield losses for this crop are based entirely on the NCLAN research (Table 4) and are 2.5 and 4.7% for Regions 4 and 5, respectively (Table 8).

4.1.2.11 Turnip

Table 6 summarizes the only experimental information regarding the exposure of this crop to ozone. In both studies (McCool et al., 1987; Heagle et al., 1985), significant yield losses were documented and models were published permitting estimates of yield loss under Ontario conditions.

In Raleigh, foliar injury appeared as chlorosis on cotyledons followed by chlorosis of a few of the oldest true leaves. After one 3.5 hour acute episode during late November, water soaking symptoms on expanded leaves of all cultivars were apparent.

In the California study (McCool et al., 1987), which was conducted under significantly different climatic conditions, using closed-top field chambers and a 12 hour seasonal ozone exposure duration, yield response very similar to that in Raleigh was obtained.

As for other crops, adjusted estimates of yield losses under Ontario exposure conditions (Regions 4 and 5) have been calculated at 3.8 and 7.4%, respectively (Table 8).

4.1.2.12 Hay

Compared to annual crops, relatively little information is available on multi-year yield responses of perennial forage crops to ozone (Temple et al., 1988).

Under controlled environmental conditions Brennan et al., (1969) evaluated the foliar response of numerous forage legumes and found that sensitivity decreased in the following order: crown vetch> alfalfa> alsike clover> white sweet clover> red clover.

In the case of clover, ozone has been shown to reduce the yield, inhibit nitrogen fixation, shift the grass/clover yield ratio in favour of the grass and accelerate the loss of clover from the combination (Blum et al., 1983). Blum et al., (1982) also reported that ozone suppressed root growth and reduced total non-structural carbohydrate reserves in roots and shoots of clover. Other studies involving the exposure of clover to ozone are summarized in reviews by Ensing and Hofstra (1982), Kochhar et al., (1980) and Bennett and Runeckles (1977).

In California, Middleton et al., (1950) estimated that 15% of the alfalfa crop was lost due to air pollution exposure in 1949. Alfalfa was also utilized in California (Oshima et al., 1976) to assess the impact of ozone via controlled, containerized studies across an ozone gradient. Other studies which review the impact of ozone on alfalfa include those by Cooley and Manning (1988) and Olszyk et al., (1986, 1988b).

In Table 6, the field studies which have been conducted to assess seasonal ozone exposure of forage mixtures are summarized. In cases involving grass/legume combinations, the data on crop yield loss reflect losses for the entire combination. In all cases, individual losses for the legume component were higher. This table also

contains the findings from chemical protectant studies conducted on numerous cultivars of several forage species in Ontario (Ensing, 1980).

On the basis of the results summarized in Table 6 and the adjustment of these data as described in Table 7, the estimates of yield losses for Regions 4 and 5 are 4.4 and 4.3%, respectively (Table 8).

4.1.3 Crops Marginally at Risk

The following seven crops have been categorized as marginally at risk. They have been placed in this category and assigned arbitrary 1 and 2% yield reduction values based on a limited amount of experimental verification or due to a lack of ozone exposure data to permit an analysis of dose:response. A brief review of each crop follows.

4.1.3.1 Grapes

Dark brown to black spotting or stipple of grape leaves was first reported in California (Richards et al., 1958) and was attributed to the presence of atmospheric ozone in the grape production areas. The symptoms, which include premature leaf senescence and abscission are commonly called "brown leaf disorder". These symptoms have been reported to be widespread on several American cultivars and French hybrids grown in vineyards throughout upper New York State (Shaulis et al., 1972). In 1973 and 1974 (Kender and Carpenter, 1974), a large number of grape cultivars and hybrids in both New York State and Ontario was assessed for oxidant injury severity. These findings prompted a four year Ontario study to ascertain the extent of the problem in terms of the severity of foliar injury development and potential adverse effects on crop yield and quality. These results (Ormrod, 1979) confirmed that the 'brown leaf' disorder of grapes is a readily recognizable problem in Ontario each year. The failure of the antiozonant chemical treatment to offer sufficient protection from foliar injury development negated the efforts to quantify any adverse yield and quality effects. Adverse yield and quality effects were, however, demonstrated in a California study (Thompson and Kats, 1970) using Zinfandel grapes in field studies with protection by charcoal filtered chambers.

In a thorough review of the effects of air pollution on grape vines, Weinstein (1984) summarized the available research and concluded that losses in fruit yield and quality can occur in the field at ambient ozone concentrations, with some cultivars exhibiting extreme susceptibility and others demonstrating remarkable tolerance. However, most observations have been associated with foliar lesions and the relationship between these symptoms and fruit yield has not been well established or studied. Based on these observations,

insufficient dose-response information was available for use in the assessment of crop risk over regions where dose variables would differ.

The work of Musselman et al. (1985) in New York, using the Concord cultivar with mature vines in open-top chambers confirmed the conclusions drawn by Weinstein (1988). The exposure of the crop to ambient ozone in combination with different dose regimes of sulphur dioxide revealed that intermittent exposures of sulphur dioxide reduced foliar tolerance of ozone. However, there were no significant effects of one or two years of ambient air filtration (ozone reduction) on vine yield, growth, maturity or soluble fruit solids.

4.1.3.2 Beet

The impact of ozone on garden beet was demonstrated in a controlled exposure in California (Ogata and Maas, 1973). Ozone symptoms appeared as a fine stipple on the upper leaf surface of oldest leaves within two days of fumigation for 2 or 3 hours per day of ozone at 150 ppb. With continued exposure, the damaged areas expanded and red anthocyanin-like pigment in the interveinal areas turned a dark purple. In advanced stages, the interveinal areas became necrotic and desiccated. Significant reductions in storage root weight were recorded with exposure durations in excess of 1 hour per day. In a more recent California study (McCool et al., 1987), utilizing closed-top field chambers with a 12 hour seasonal mean ozone statistic (9 ozone concentration regimes), yield reductions of 6.6 and 11.1% were calculated from a linear model for 12 hour seasonal means of 40 and 50 ppb, respectively.

4.1.3.3 Burley Tobacco

Weather fleck results in moderate damage to the burley tobacco crop in southwestern Ontario each year (Anderson and Welacky, 1983). The loss is attributed to the shattering of flecked leaves during curing and stripping operations. There is also potential for adverse effects on quality, as chemical characteristics are affected (Huang et al., 1976; Menser et al., 1977). In 1980 and 1981, visual estimates of weather fleck damage on 13 Burley cultivars at Harrow, Ontario revealed mean damage on leaves 1-12 ranging from 3.0 to 7.2% in 1980 and 0.2 to 9.4% in 1981 (Anderson and Welacky, 1983). Seven-hour seasonal mean ozone concentrations at Windsor (32 km from Harrow) during 1980 and 1981 were 48 and 46 ppb, respectively. Although controlled, seasonal ozone exposures have not been undertaken with this tobacco type, there is little doubt that direct yield reductions similar to those documented for flue-cured tobacco (Heagle et al., 1987a) are occurring throughout the main tobacco

production areas which are located in southwestern Ontario, close to Lake Erie.

4.1.3.4 Cucumber, Squash, Melon, Pumpkin

Chlorotic mottle of leaves, early leaf senescence, and, possibly increased susceptibility to diseases are problems incurred by cucurbit species in southern Ontario each year due to oxidant exposure (Ormrod, 1980). In 1979 and 1980 studies were undertaken to assess the relationship between foliar symptom development and yield suppression in cucumber. The studies utilized a number of different locations using two different chemical protectants. The results (Ormrod, 1980, 1981) revealed that at some locations there was a cultivar response to chemical protection. The results in 1979 were less conclusive than those of 1980 when overall reductions of 13% were recorded, with one location (all cultivars) yielding 15% less in unprotected cucumber plots compared to those provided with antioxidant protection.

Studies on muskmelon and watermelon in Indiana also have confirmed the role of ozone in extensive foliar injury development and reduced fruit yield (Snyder et al., 1988; Eason et al., 1986). In open-top chambers with and without carbon filtration significant yield reductions of 21.3 and 20.9% for marketable fruit weight and fruit number were documented for 'Superstar' muskmelon (Snyder et al., 1988). Ambient ozone was measured during this study but the concentrations were not averaged for the season. However, from the graphical presentation of the average hourly values, it is estimated that the seasonal means were in the range of 40-50 ppb.

4.1.4 Crops Potentially at Risk

Adverse ozone effects on foliar injury and yield loss have been documented for a number of other crops, including: radish, pea, carrot, celery, cabbage, cauliflower, eggplant, pepper, sunflower, peanut, field corn, strawberry, spring barley, oats and apple. In the case of celery, pepper, strawberry, spring barley, field corn and leaf lettuce, the studies (Takemoto et al., 1988; Temple et al., 1985; Heagle et al., 1979b; Kress and Miller, 1985; McCool et al., 1987 have been conducted in an NCLAN style, utilizing either open or closed-top chambers with constant or proportional ozone dispensing under field conditions. However, in each case, the threshold for adverse yield effects was either above the average seasonal mean of 50 ppb encountered in Ontario or the results were not statistically significant. It should be noted that in the case of field corn, one of the most significant field crops in Ontario, the research results have indicated detectable yield losses in the <1-3% range for seasonal means as low as 60 ppb. In no case have any experimental

results confirmed losses below this level. In spite of these findings, the NCLAN summaries have utilized the Weibull model to predict regional yield losses at seasonal means of 40 and 50 ppb.

Sensitivity to ozone also has been demonstrated for the other crops; however, except for peanut (Ensing et al., 1985), the experimental studies have been limited to short duration, foliar effect or biomass evaluations which do not permit an assessment of yield impact under field conditions. The peanut study in Ontario did document an adverse impact on yield, but this was limited to one of several cultivars tested using chemical protectants.

On the basis of the foregoing information, and the absence of any other supporting data, these crops were not included in the AT RISK or MARGINALLY AT RISK categories in the 1989 assessment. Other crops not included in the 1989 assessment were those grown under glass. Greenhouse crops represent a significant contribution to Ontario's agricultural productivity: however, there is insufficient information at this time to assess the potential benefits from an ozone control program.

4.2 Forests

There are many different parameters and limiting factors which must be considered in evaluating and quantifying the effects of ozone on forest trees compared to agricultural crops. Forest tree species are long-lived, perennial plants that are exposed to ozone repeatedly during the year and over several years and, unlike agricultural crops, are not usually subjected to fertilization, irrigation, pesticide application or other cultural practices that can moderate their response in the field. Assessment of adverse effects of ozone on seedlings or young trees can be evaluated under controlled conditions. However, the large size of trees at maturity precludes experimental dose dispensing in exclusion chamber studies or the use of protective antioxidant sprays. These factors have limited the assessment of ozone impact to visual observations of foliar injury, and radial and height growth characteristics of individual trees in the stand. Where growth analysis is undertaken from different stands on the basis of air quality gradients, the data must then be considered in terms of edaphic and climatic site variation and related to ozone dose information, where available. Another complicating factor which must be addressed when assessing the overall impact of ozone on forest growth and yield is the process of inter- and intra-plant species competition and possible alterations in successional processes and species composition. In this regard, an adverse effect on the growth or survival of one tree species could have either a beneficial or detrimental effect on the growth or survival of another species, thereby increasing or

decreasing the total productivity of a mixed forest stand. However, as indicated by Treshow (1970), ecosystems usually are delicately balanced with a structure which may depend on a few critical species and any disruption in this balance after prolonged environmental stress could lead to very rapid, irreversible changes.

On the basis of controlled ozone exposures, many tree species indigenous to Eastern North America are classified as being susceptible to foliar ozone injury (Davis and Wood, 1972; Davis and Coppolino, 1974; Davis and Wilhour, 1976; Skelly, 1980). Direct injury to tree foliage by ozone has been demonstrated repeatedly in experimental situations, and in nature as well. Concentrations of ozone, at least in some forested areas, are sufficient to cause injury (Linzon, 1973; Miller, 1983; Skelly, 1980). As indicated, these ozone effects can alter the productivity, successional patterns, and species composition of forests (Smith, 1980) and enhance activity of insect pests and some diseases (Woodwell, 1970). The status concerning ozone-induced effects on temperate and Mediterranean forest tree species, communities and ecosystems was summarized by Skelly (1980), who concluded it is possible that primary productivity, energy resource flow patterns, biogeochemical patterns and species successional patterns may all be challenged by oxidant air pollution.

In the most recent and thorough review undertaken to date, Pye (1988) provided a critique of available experimental approaches, summarized tree response data from controlled fumigations and discussed the difficulties in extrapolating experimental findings to regional, economic damage estimates.

In terms of experimental design, indoor growth chambers, greenhouses and continuously stirred tank reactors (CSTRs) have been the most commonly employed forest research technique. Outdoor exposures have utilized open-top chambers and occasionally chamberless designs. Although the latter technique offers improvement in air flow, the open-top chamber, despite alterations in temperature, humidity and air flow, appears to provide the most consistent data for yield loss determination.

From a biochemical and physiological response basis, Pye (1988) provides a brief review of the current understanding of ozone effects. "At the biochemical level ozone oxidizes sulfhydryl and fatty acid double bonds, increases membrane permeability, and disrupts membrane-bound photosynthetic systems (Guderian et al., 1985; Mudd, 1984). Foliar sugar and polysaccharide levels are lowered as well (Miller et al., 1969). At the physiological level net photosynthesis is reduced, dark respiration is increased (Barnes, 1972), and C transport to roots is lowered (McLaughlin and McConathy, 1983). Other physiological impacts include coincident

and long-term reductions in stomatal conductance (Hill and Littlefield, 1969, Reich and Amundson, 1985; Coyne and Bingham, 1982), accelerated leaf senescence (Reich, 1983; Jensen, 1982; Noble and Jensen, 1980; Reich and Lassoie, 1985), reduced root/shoot ratio (Hogsett et al., 1985; Chappelka and Chevone, 1986) and increased foliar leaching (Rehfuess et al. 1982)."

Before any attempt is made to extrapolate data from controlled experimental studies to the forest stand, a number of other factors must be assessed. These were summarized by Pye, (1988) and include changes in stand regeneration, mortality, growth rates and wood quality (strength and pulp yield). It is also pointed out that caution must be exercised in extrapolations based on foliar injury assessments. As was the case with agronomic species, tree growth reduction can occur without visible symptoms (Reich and Amundson, 1984, 1985; Reich et al., 1986); visible symptoms can occur without growth impacts (Jensen and Dochinger, 1974, McClenahen, 1979; Patton, 1981) and rankings of species susceptibility based on growth measures do not always correlate with those based on foliar symptoms (Jensen, 1973; Jensen and Masters, 1975; Wilhour and Neely, 1977; Kress and Skelly, 1982). This latter finding is important as lack of growth reductions with a decreased photosynthetic area suggests compensations in carbon allocation and respiration. Another factor is the possibility that subtle growth reductions were missed due to experimental variability and inadequate error control (Wang et al., 1987).

In his review, Pye (1988) evaluated biomass growth, height growth and photosynthesis utilizing data from 25 published experiments on seedlings of 43 tree species and hybrids. On the basis of these studies, ozone has been clearly demonstrated to reduce tree growth significantly at concentrations common to many areas of the U.S. (seasonal means from 40-60 ppb). These concentrations also are common throughout most of southern Ontario. Pye also points out that in the growth response analysis, the statistical power of the study designs is critical for exposures near ambient concentrations. To date, problems with statistical design, genetic and environmental variability and exposure duration have prevented the detection of significant growth reductions below about 9%. In addition to the comprehensive review of the experimental data, Pye (1988) has summarized the factors which limit the extrapolation of these short term data to longer growth cycle conditions, to mature trees and subsequently to stand level yield. These difficulties have been briefly summarized below:

<u>Extrapolating from Short Term to Long Term Exposures</u>

- as trees vary in their response to and recovery from ozone over time, the length and timing of the exposure and subsequent data

collection can significantly alter the experimental outcome and conclusions

- as leaf phenology differs significantly between determinate and indeterminate tree species, the impact of ozone for a short duration will vary, depending on species type and exposure timing

- as conifers retain their foliage for periods well in excess of a year, the impact of a short duration ozone exposure during only part of this period is of limited value in terms of the full life-span of the foliage

Extrapolating from Seedlings to Mature Trees

- as the balance (ratio) between metabolically active (photosynthetic) and catabolically (respiration) dominant tissues decreases with age, the impact of ozone early in the life of a tree may not directly translate into equivalent effects later in the growth cycle

- as the micro environment in which a leaf grows affects its morphology, resulting in large differences within a mature canopy, the impact of ozone on a uniform set of seedling leaf types may not represent the complete range of foliar response within a mature canopy

- as water and nutritional transport and storage differ between young and old trees as cambial reserves increase, this may affect daily and seasonal patterns of stomatal conductance and influence ozone uptake and impact

Extrapolating from Individual Trees to Forest Stands

- as the distribution of tree sizes in a stand directly affects timber value, and as ozone impacts may directly or indirectly affect this gradient, stand volume and size distribution could be disproportionately altered; of key concern is whether stand processes will compensate for or amplify impacts on individual trees

- as ozone susceptibility of dominant and suppressed trees within a stand will vary depending on a host of phenotypic and genotypic factors, ozone impact assessment at the stand level requires a more comprehensive understanding of stand dynamics, microclimate, genetic composition and site quality than is provided from seedling level experimentation

In order to overcome some of the limitations which have been described for controlled environment, single species and seedling age research, other approaches to the evaluation of ozone impacts have focused on regional scale growth analysis studies (Ohmart and Williams, 1979; McLaughlin et al., 1983; McLaughlin, 1985; Adams et al., 1985; Cook, 1985 and Benoit et al., 1982) and evaluations of ozone levels in forested areas (Pinkerton and Lefohn, 1987). In only a few cases where ozone levels far exceed those normally encountered in Ontario and where ozone injury symptoms have been observed and documented during the past 20 years, have significant ozone related decreases in radial growth been detected (Peterson et al., 1987; Miller, 1983). Definitive conclusions concerning the role of ozone in recorded growth reductions are still not possible in other less severely impacted areas of North America due to the difficulty involved in experimental resolution and in partitioning these effects from other variables that also affect tree growth.

In Ontario, foliar symptoms associated with ozone injury to white ash and Eastern white pine have been observed by MOE staff extensively throughout ozone Regions 4 and 5 and occasionally in Region 3 (Figure 1). Reductions in radial growth of a number of hardwood species also have been documented throughout these areas (MOE, 1989). However, until such time as additional studies are undertaken, the role of ozone in these documented forest growth reductions can not be quantified. It should be noted though, that based on the trend in Ontario of decreasing ozone levels in a north-south gradient (Figures 1 - 3), any impact of ozone on commercial forestry, which predominates in the northern areas of the province, should be much less than in rural areas of southern Ontario. Although economic impacts in southern Ontario can not be reliably quantified at this time, there is mounting research evidence that ozone concentrations similar to those experienced in southern Ontario have the potential to affect productivity of a large number of sensitive hardwood and softwood species, many of which have significant commercial value as fine furniture and veneer woods. There is also a potential impact of hybrid poplar plantings. In the latter case, impacts on this relatively new area of intensive forest management will be easier to assess in future years as the body of research which is mounting on the ozone sensitivity of poplars will be more easily extrapolated to field effects due to the short term nature of this mono-culture type forest 'crop'.

4.3 Ornamentals

There have been a number of experimental studies designed to examine the effect of ozone on woody and herbaceous ornamental plants. Some of the herbaceous species examined include: petunia (Craker, 1972), carnation (Feder, 1970), geranium (Feder, 1970), poinsettia (Manning et al., 1973), chrysanthemum (Klingaman and Link, 1975; Brennan and

Leone, 1972), turfgrass (Wilton et al., 1972) and begonia, coleus, snapdragon, marigold, celosia, impatiens, salvia (Adedipe et al., 1972). The results of these studies have shown a considerable degree of cultivar sensitivity with effects ranging from growth depression, alteration of plant habit, retardation of floral initiation as well as reductions in flower production. However, in many of these studies, ozone exposure concentrations were unrealistically high or of short duration, making extrapolation of impact to natural exposure under field conditions difficult. Even if these studies had been conducted under exposure conditions characteristic of those encountered in the field, it would be difficult to assess the economic impact of these aesthetic impacts.

Experimental progress in the case of woody ornamentals has been more advanced than for herbaceous species. This has resulted from the dual role of many species as both ornamental and forest stock. In their role as ornamentals, the majority of trees and shrubs are planted as single specimens with full exposure to ambient air. This contrasts with the forest situation where a variety of canopy and stand factors must be quantified before valid extrapolations to natural settings can be made. As a result, much of the forestry oriented experimental research that has been conducted on tree seedling response to ozone has particular value in terms of ornamental effects.

In a review of the tree seedling research reported up to 1986, Pye (1988) summarized ozone effects on biomass, height and photosynthesis for 43 tree species or hybrids. On the basis of this summary, which was based on an evaluation of 25 controlled exposure, experimental studies, and on additional work which has been published since that time (Chappelka et al., 1988a, 1988b; Reich et al., 1987, 1988; Elliott et al., 1987) there is strong evidence that ozone exposures common to most areas of the U.S. and Ontario are causing growth reductions in many sensitive landscape trees.

Tree species common to Ontario which have demonstrated ozone sensitivity (biomass, height, photosynthesis) under controlled ozone exposure conditions include: maples (sugar, silver, red), ash (white, green), spruce (white), white pine, poplar (hybrid), cottonwood, cherry, walnut, sycamore, white birch and red oak. Although in many of the experimental studies, ozone impacts varied significantly (reductions and stimulations), the response to seasonal exposures in the 40-60 ppb range for over half of the studies was reported as at least nominal growth reductions (Pye, 1988).

On the basis of these findings and the similarity in the range of ozone exposures in Ontario to those of many of the research studies, it is estimated that ornamental nursery supply operations in

southern Ontario (Ozone Regions 4 and 5), including Christmas tree production, suffer an annual productivity loss of about 5% with a range of 2-7%, depending on exposure and climatic variation. These estimates are well below the experimental detection limit for growth effects on the most sensitive species which was determined (Pye, 1988) to be approximately 9%. Given the relatively limited species testing that has been conducted to date, and the high likelihood that other species not yet evaluated are experiencing similar adverse growth effects, these conservative loss estimates can conservatively be applied to all ornamental woody species cultivated for sale in Ontario.

There is also considerable evidence that ozone can injure many annual and perennial grass species commonly utilized in turfgrass production in Ontario (Elkiey and Ormrod, 1980; Richards et al., 1980). Although these studies have not examined growth/productivity impacts, the similarity of these species to the forage species already evaluated in Section 5.1.2.12 would support the application of an average growth reduction similar to that for ornamental trees (5% with a range of 2-7%).

5.0 ECONOMIC BENEFITS OF OZONE CONTROL

On the basis of the crop loss functions and estimated impact on ornamentals provided in this document, Donnan (1989) has calculated the benefits that would accrue to Ontario farmers and those involved in the supply of ornamental trees and nursery sod and Christmas trees. The values and corresponding market information for all affected crops in Regions 4 and 5 are presented in Tables 10 and 11 and are summarized in Table 12.

For ornamentals and Christmas tree production, the potential benefits are described in Table 13. A summary of the complete economic benefit package which ranges from \$16.6 - \$69.6 million annually, with an average of \$44.5 million is shown in Table 14.

6.0 SUMMARY AND CONCLUSIONS

This report summarizes the results of extensive efforts which have been undertaken in Ontario to assess the impact of ozone and other oxidants on all types of terrestrial vegetation and to provide a scientific basis for the derivation of economic benefits from an ozone control program. Other objectives were to assess the response of vegetation to other regionally transported pollutants, to multiple pollutant exposures and to assess the adequacy of Ontario's existing 1 hour ozone criterion of 80 ppb, in terms of providing protection against adverse impacts on crops, ornamentals and forests in the province.

In the case of agricultural crops, the estimation of production losses was accomplished by a thorough review of the scientific literature as well as many unpublished government and university reports and conference proceedings and the development of a database for crop response to 7-hour seasonal mean ozone concentrations of 40 and 50 ppb. A total of 19 crops was assessed in this manner, and for 12 of the 19, a multi-component adjustment factor approach was utilized in the estimation of crop loss due to ozone exposure in Ontario to compensate for geographic, agronomic and experimental variability in the research results. Based on these findings and an analysis of the Ontario ozone database, it was subsequently determined by Donnan (1989) that agricultural field crop productivity in Ontario would increase by an average of $39 million with a range of $14 to $61 million per year with reductions in ozone to seasonal mean concentrations of less than 40 ppb. Statistical analysis of the ozone data from 1974-1988 revealed that this could be achieved by control efforts designed to meet the existing 1 hour ambient air criterion of 80 ppb.

In the case of ornamentals, including landscape trees, turfgrass and Christmas trees, productivity losses were more subjectively estimated at an average of 5% with a range of 2-7% in the southern portion of the province experiencing ozone seasonal means in the 40-60 ppb range. The economic impact of these losses has been estimated (Donnan, 1989) at $6 million with a range of $2 to $8 million per year, again based on ozone reductions to achieve the existing 1 hour ambient air criterion of 80 ppb.

Although foliar injuries have been documented on many forest species in Ontario, the state of knowledge at this time was insufficient to develop a reliable estimate of productivity losses. However, it has been noted in the report that in Ontario, the major portion of the forest industry is located in an area of the province where ozone levels normally are lower than in the agricultural production areas of southern and central Ontario.

On the basis of this assessment, which formed the basis for estimates of productivity losses to crops and ornamentals which have a total economic benefit value of about $45 million and a range in benefits from approximately $17 to $70 million per year, it is concluded that control efforts should be directed towards the reduction of ozone levels in Ontario.

An evaluation of the impacts of other oxidants, including peroxyacetyl nitrate (PAN) and nitrogen dioxide failed to indicate any concern for direct impacts on vegetation at existing air quality levels. In the case of multiple exposures involving ozone and sulphur dioxide or acid rain/fog, there has been field type research that appears to rule out any significant enhancement of crop

productivity losses. However, interactions involving some of these oxidants with ozone can not be ruled out due to a dearth of research conducted under growing season, field conditions. In the case of trees, the role of pollutant interactions which have been documented under controlled experimental conditions utilizing juvenile experimental material, has not been clarified for mature trees nor forest stands.

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FIGURE 1 CONTOURS OF AVERAGE SEASONAL 7 HOUR MEAN OZONE CONCENTRATIONS IN ONTARIO : 1974-88

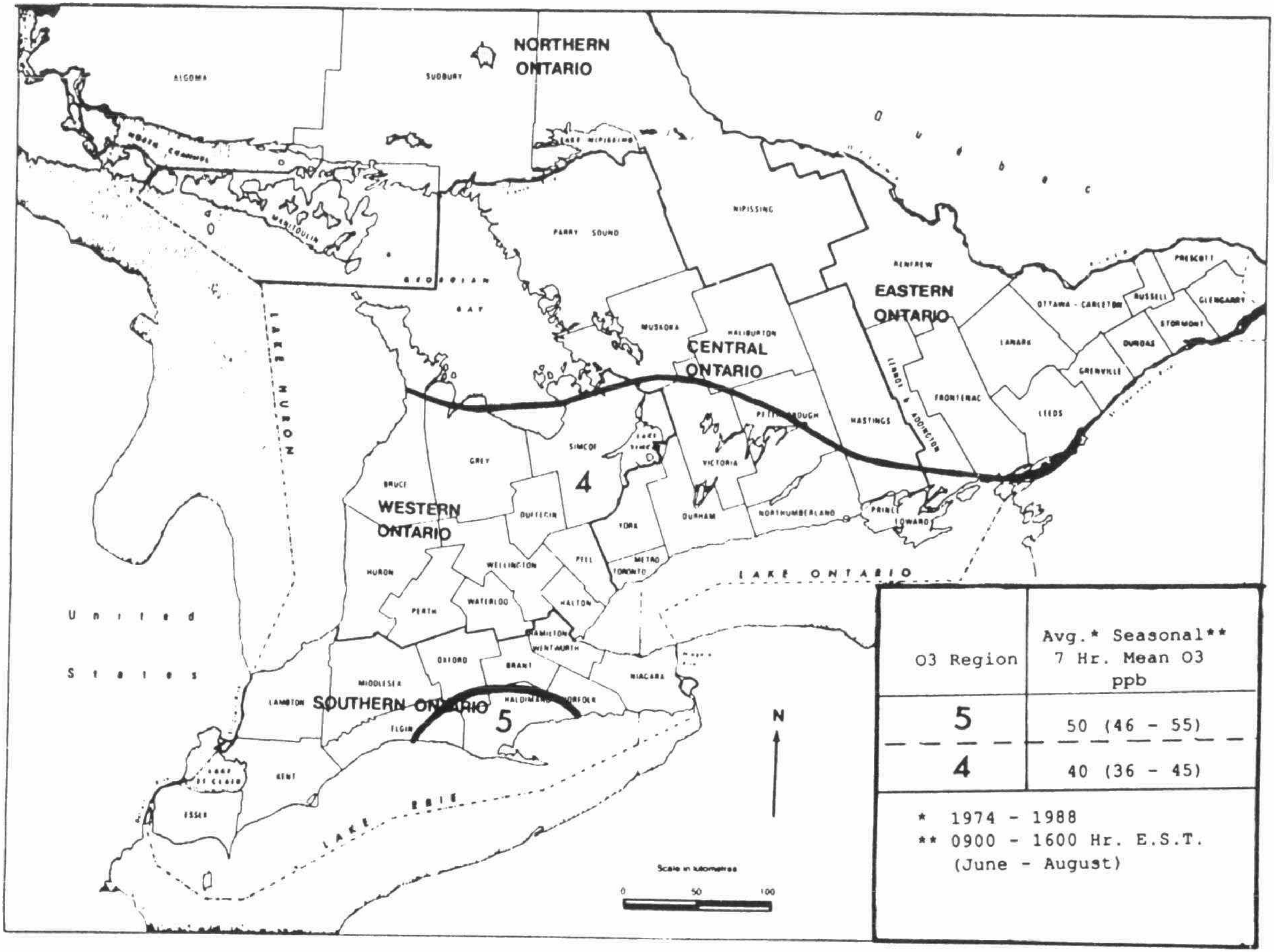


FIGURE 2 CONTOURS OF MAXIMUM SEASONAL 7 HOUR MEAN OZONE CONCENTRATIONS IN ONTARIO : 1974-88

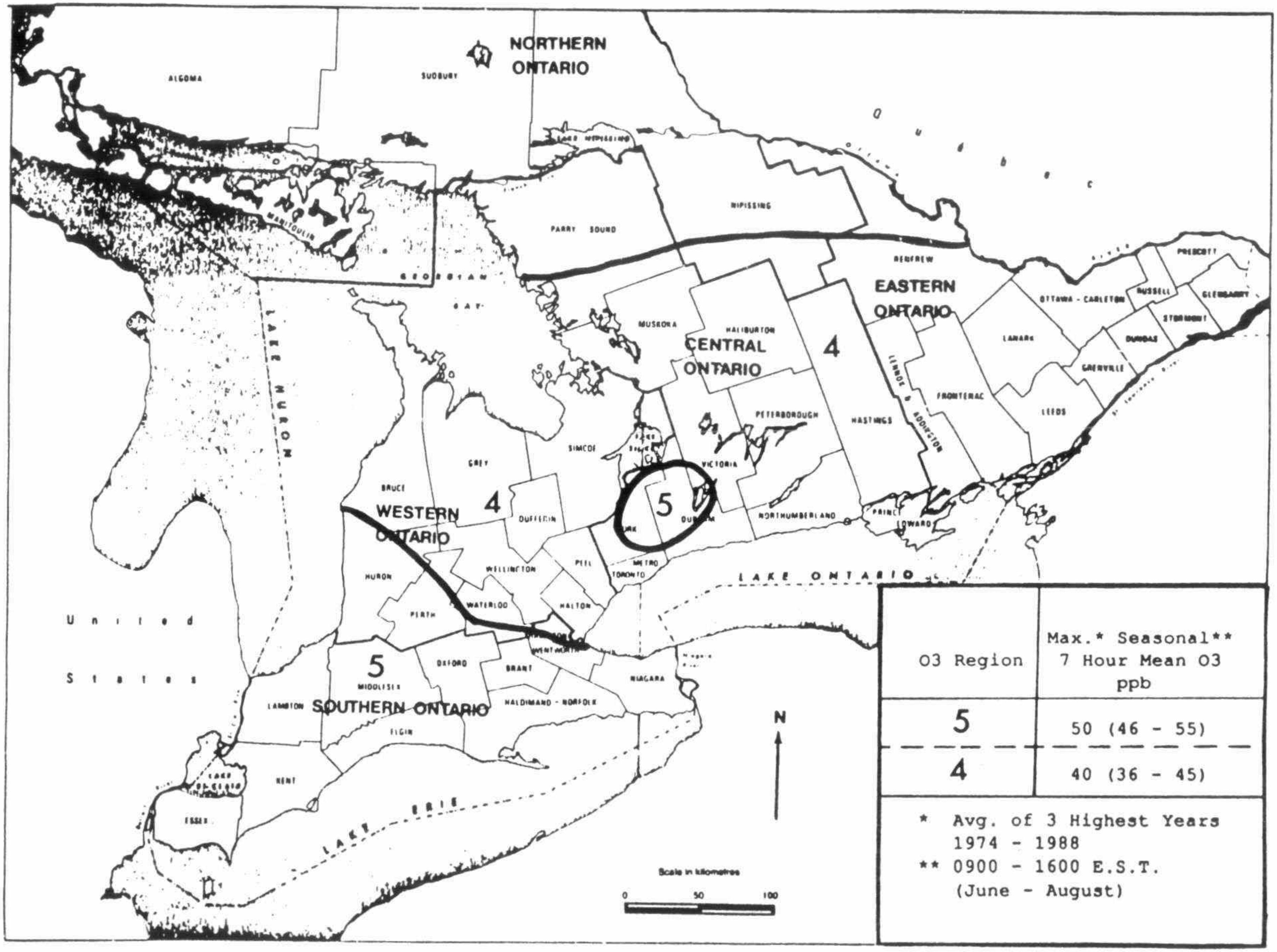
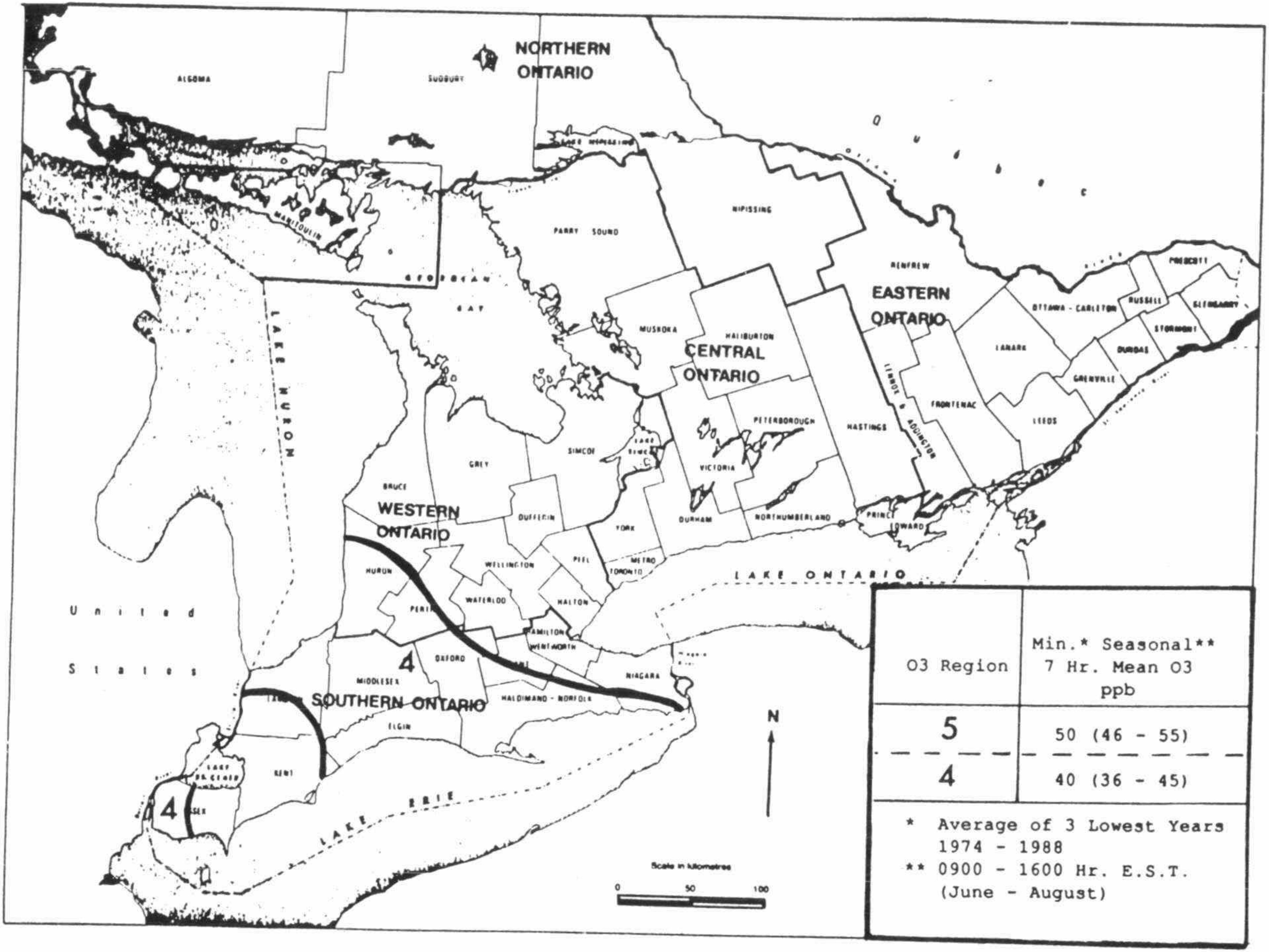


FIGURE 3 CONTOURS OF MINIMUM SEASONAL 7 HOUR MEAN OZONE CONCENTRATIONS IN ONTARIO : 1974-88



O3 Region	Min.* Seasonal** 7 Hr. Mean O3 ppb
5	50 (46 - 55)
4	40 (36 - 45)

* Average of 3 Lowest Years 1974 - 1988

** 0900 - 1600 Hr. E.S.T. (June - August)

FIGURE 4 CONTOURS OF SEASONAL 7 HOUR MEAN OZONE CONCENTRATIONS IN ONTARIO : 1988

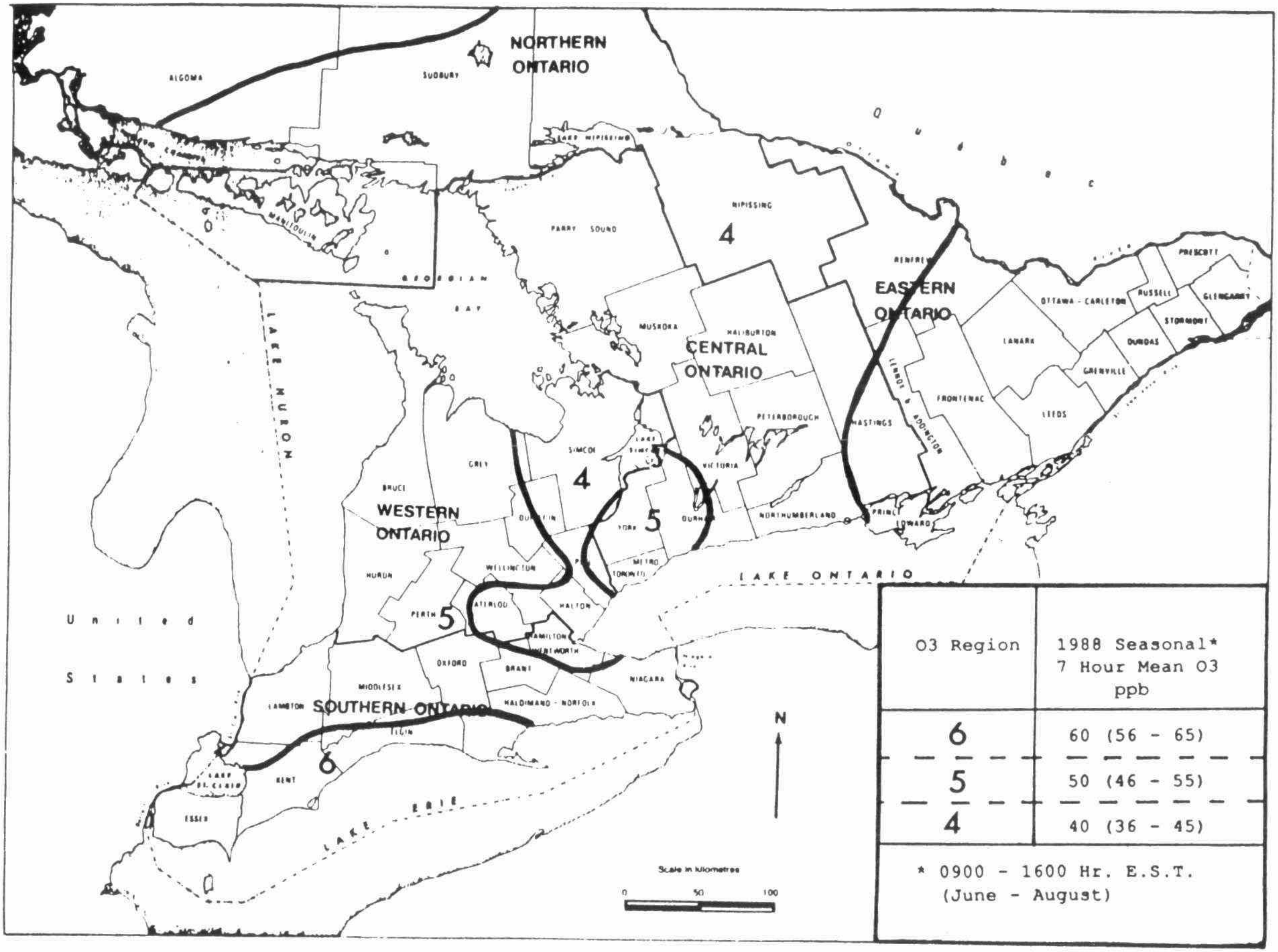


FIGURE 5 STATISTICAL RELATIONSHIP BETWEEN MAXIMUM HOURLY AND SEASONAL MEAN OZONE CONCENTRATIONS IN ONTARIO : 1974-88

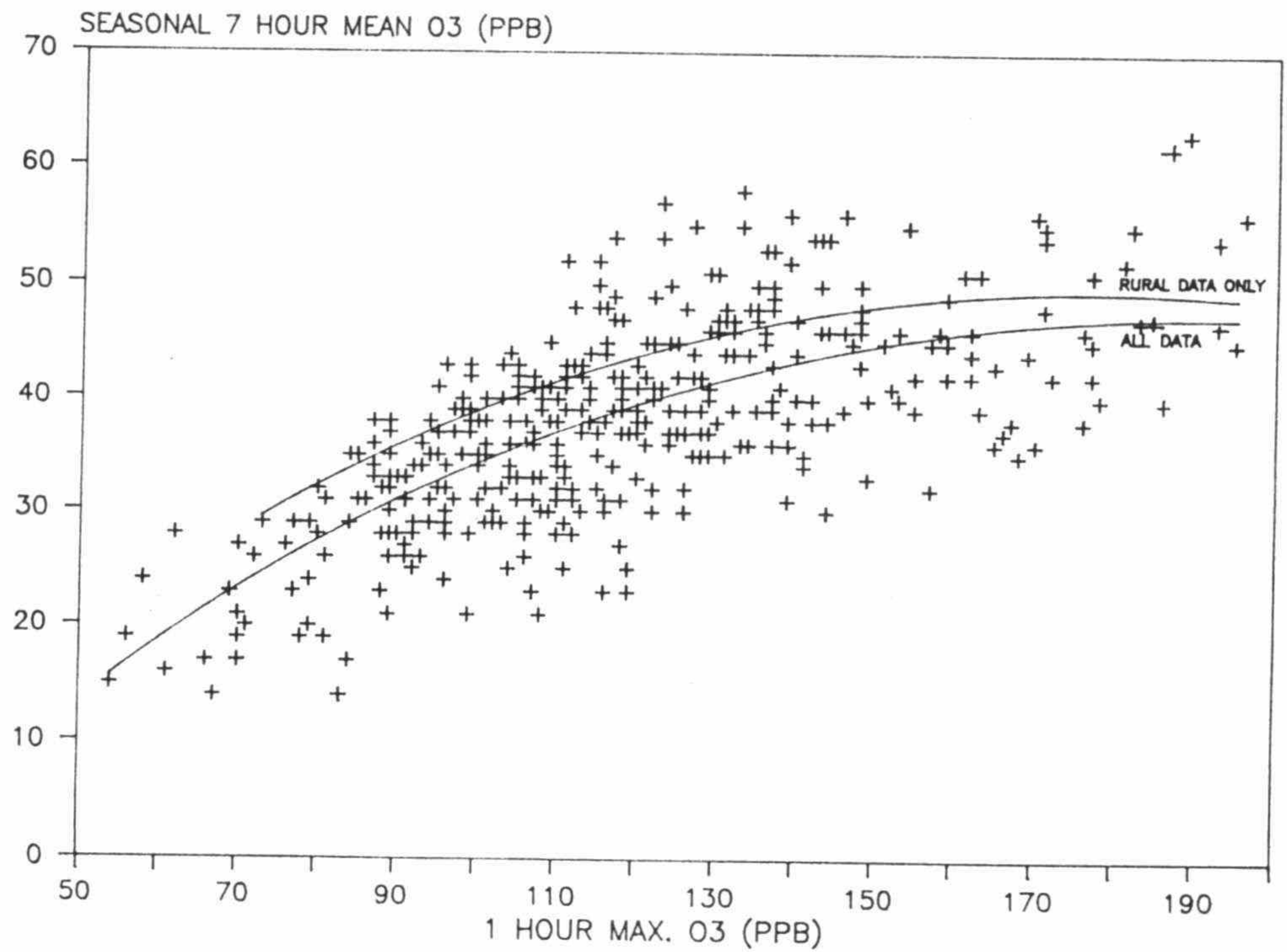


FIGURE 6 TREND IN SEASONAL 7 HOUR MEAN OZONE CONCENTRATIONS AT 2 RURAL SITES IN ONTARIO : 1974-88

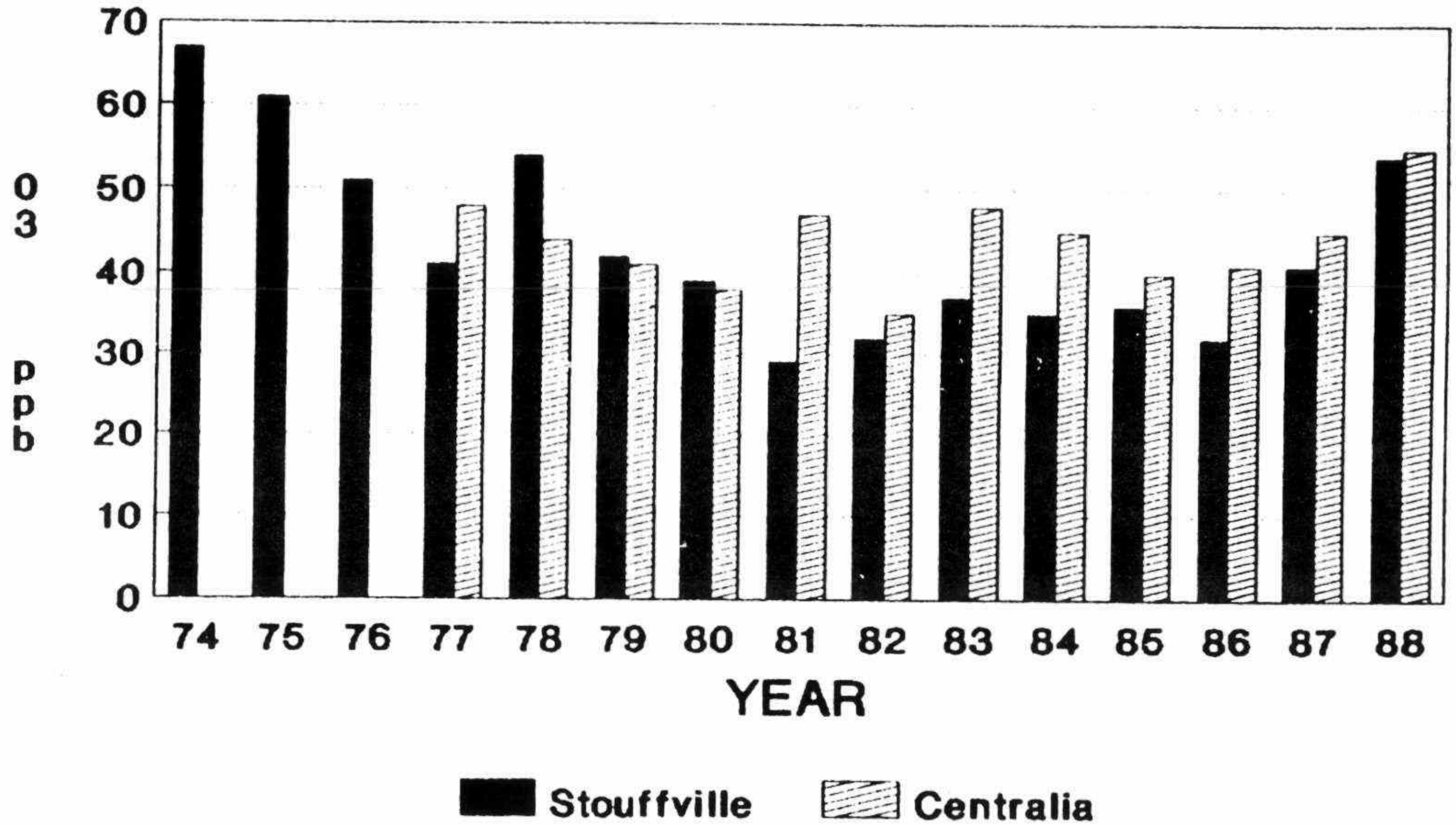


FIGURE 7 ADJUSTMENT FACTOR CALCULATION FOR YIELD LOSS TO AGRICULTURAL CROPS

$$
\text{A. F.} = \frac{\left(\overbrace{\left[\frac{(VDR_1 x RWF_1) + (VDR_2 x RWF_2) + (VDR_3 x RWF_3)}{(TVD)} \right]}^{\text{(GEOGRAPHIC VARIABILITY)}} + \overbrace{\left[\left(\frac{CT}{CF_c}\right) x100 + \frac{(VD_i x SMWF_i) + (VD_{ni} x SMWF_{ni})}{(TVD)} \right]}^{\text{(AGRONOMIC VARIABILITY)}} + \overbrace{\left[\left(\frac{TVD}{CF_{tvd}}\right) x100xEWF_{tvd} + \left(\frac{VD_m}{TVD}\right) x100 + \left(\frac{VD_{ss}}{TVD}\right) x100xEWF_{ss} \right]}^{\text{(EXPERIMENTAL VARIABILITY)}} \right)}{1000}
$$

TERM DEFINITION:

VDR_1	Valid data from geographic Region 1 (Ontario and NE-U.S.)
VDR_2	Valid data from geographic Region 2 (SE, Mid-W, WU.S.)
VDR_3	Valid data from geographic Region 3 (SW U.S.)
RWF_1	Region 1 weight factor = 100
RWF_2	Region 2 weight factor = 50
RWF_3	Region 3 weight factor = 10
TVD	Total valid data per crop
CT	No. different cultivars/cultivars/species tested
CF_c	Confidence factor for cultivars = 20
VDi	Valid data from irrigated studies
VD_{ni}	Valid data from non-irrigated studies
$SMWF_i$	Soil moisture weight factor - irrigated studies= 1
$SMWF_{ni}$	Soil moisture weight factor - non-irrigated studies = 100
CF_{tvd}	Confidence factor for valid data (total) = 120
EWF_{tvd}	Experimental weight factor -size of dataset = 3
VD_m	Valid data from dose response functions(models)
VD_{ss}	Statistically significant valid data
EWF_{ss}	Experimental weight factor - significant data=3

TABLE 1

RELATIONSHIP BETWEEN ANNUAL 1 HOUR MAXIMUM AND SEASONAL 7 HOUR MEAN OZONE CONCENTRATIONS IN ONTARIO : 1974 -1988

MAXIMUM RECORDED* 1 HR. O3 (PPB)	PREDICTED** SEASONAL*** 7 HR. MEAN O3 ALL SITES MEAN (PPB)	(95% C.I.)	RURAL SITES MEAN (PPB)	(95% C.I.)
80	27	(26-28)	32	(29-35)
90	31	(30-32)	36	(33-38)
100	34	(33-35)	39	(37-40)
110	37	(36-38)	41	(40-43)
120	40	(39-40)	44	(42-45)
130	42	(41-43)	46	(44-47)
140	44	(43-45)	47	(46-49)
150	45	(44-46)	48	(47-50)
160	46	(45-47)	49	(48-51)
170	47	(45-48)	50	(48-52)
180	47	(45-49)	50	(47-53)

* January-December,24 hours per day

** Statistical regression based on second degree polynomial

All sites: Seasonal Mean = $-0.00185(\text{Annual Max. O3})^2 + 0.683(\text{Annual Max. O3}) - 15.7204$
r=0.71*** n=389

Rural sites: Seasonal Mean = $-0.00184(\text{Annual Max. O3})^2 + 0.6567(\text{Annual Max. O3}) - 8.6683$
r=0.63*** n=117

*** June-August from 0900-1600 EST (7hr/d)

TABLE 2

COMPARISON OF SEASONAL MEAN AND HOURLY OZONE CONCENTRATIONS BASED ON 7 AND 12 HOURLY DOSE STATISTICS FOR SELECTED RURAL AND URBAN SITES IN SOUTHERN ONTARIO: 1974-1988

LOCATION	NO YRS. MONITORED (1974-88)	URBAN/ RURAL	AVERAGE* SEASONAL MEAN O3		AVERAGE* NO. HRS.****O3> 80ppb		100ppb		120ppb	
			7HR**	12HR***	7HR	12HR	7HR	12HR	7HR	12HR
WINDSOR	15	U	45	44	61	101	18	29	5	7
MERLIN	10	R	42	41	35	61	7	14	1	3
LONDON	14	U	42	40	30	48	6	9	1	2
CENTRALIA	12	R	44	43	39	69	6	13	1	1
SIMCOE	14	R	51	50	54	97	12	22	2	3
TORONTO a	15	U	39	37	44	66	15	22	5	7
STOUFVILLE	15	R	43	42	44	69	16	25	8	12
DORSET	7	R	37	36	16	26	1	2	0	0
SUDBURY	13	U	24	24	1	2	<1	1	0	0
OTTAWA	12	U	31	28	6	10	<1	1	0	<1

a SITE AT DOWNTOWN TORONTO LOCATION (BREADLEBANE)
* AVERAGE OF ALL YEARS MONITORED
** JUNE - AUGUST FROM 0900 - 1600 EST (7 HOURS PER DAY)
*** JUNE - AUGUST FROM 0800 - 2000 EST (12 HOURS PER DAY)
**** DURING THE RESPECTIVE 7 AND 12 HOUR PERIOD FROM JUNE-AUGUST

TABLE 3

SUMMARY OF OZONE CONCENTRATIONS (ppb) AT SELECTED RURAL AND URBAN LOCATIONS IN SOUTHERN ONTARIO: 1988 VS 1974-88

LOCATION	NO. YRS. MONITORED (1974-88)	URBAN/ RURAL	MAX.* 1 HR O3 1988	MAX.* 1 HR O3 AVG.*** (RANGE) 1974-88	7 HR SEASONAL MEAN** O3 1988	7 HR SEASONAL MEAN** O3 AVG.*** (RANGE) 1974-88	NO HOURS**** O3 > 80 ppb 1988	NO HOURS**** O3 > 80 ppb AVG.*** (RANGE) 1974-88	NO HOURS**** O3 > 100 ppb 1988	NO HOURS**** O3 > 100 ppb AVG.*** (RANGE) 1974-88	NO HOURS**** O3 > 120 ppb 1988	NO HOURS**** O3 > 120 ppb AVG.*** (RANGE) 1974-88
WINDSOR	15	U	188	148 (104 - 274)	62	45 (34 - 62)	173	61 (12 - 173)	68	18 (1 - 68)	26	5 (0 - 26)
MERLIN	10	R	133	112 (87 - 137)	58	42 (28 - 58)	173	35 (1 - 173)	45	7 (0 - 45)	8	1 (0 - 8)
LONDON	14	U	137	117 (99 - 166)	53	42 (36 - 53)	95	30 (5 - 95)	28	6 (0 - 28)	4	1 (0 - 8)
CENTRALIA	12	R	127	120 (100 - 137)	55	44 (35 - 55)	114	39 (8 - 114)	28	6 (0 - 28)	3	1 (0 - 3)
SIMCOE	14	R	196	129 (99 - 196)	56	51 (43 - 56)	109	54 (20 - 113)	41	12 (0 - 41)	5	2 (0 - 12)
TORONTO a	15	U	159	133 (86 - 201)	42	39 (28 - 60)	71	44 (5 - 162)	20	15 (0 - 98)	5	5 (0 - 49)
STOUFFVILLE	15	R	161	145 (84 - 312)	51	43 (29 - 67)	88	44 (1 - 151)	21	16 (0 - 97)	8	8 (0 - 69)
DORSET	7	R	195	107 (80 - 195)	45	37 (32 - 45)	64	16 (0 - 64)	6	1 (0 - 6)	0	0 (0)
SUDBURY	13	U	84	90 (70 - 118)	36	24 (14 - 36)	0	1 (0 - 3)	0	<1 (0 - 1)	0	0 (0)
OTTAWA	12	U	127	95 (76 - 127)	35	31 (27 - 39)	20	6 (0 - 24)	3	<1 (0 - 3)	0	0 (0)

a SITE AT DOWNTOWN TORONTO LOCATION (BREADLEBANE)

* MAXIMUM 1 HOUR CONCENTRATION (JAN - DEC: 0000-2400 EST)

** JUNE - AUGUST FROM 0900 - 1600 EST (7 HOURS PER DAY)

*** AVERAGE OF ALL YEARS MONITORED

**** DURING PERIOD OF JUNE - AUGUST FROM 0900 - 1600 EST

TABLE 4

SUMMARY OF GROWING SEASON O3 DATA FOR NAPS STATIONS IN EASTERN CANADA : 1976 -85

LOCATION	YEAR	NO. SITES	AVG.* MAX. 1 HR. O3	AVG.* SEASONAL MEAN** O3	AVG.* NO. HRS. O3 > 80ppb	100ppb	120ppb
			.........ppb	....			
HALIFAX NOVA SCOTIA	1976	1	70	14	0	0	0
	1977	2	110	22	5	3	1
	1978	1	90	34	6	0	0
	1979	1	90	32	8	0	0
	1980	1	50	13	0	0	0
	1981	1	30	9	0	0	0
	1982	1	120	38	6	5	2
	1983	2	40	14	0	0	0
	1984	1	40	19	0	0	0
	1985	2	60	17	0	0	0
ST. JOHN NEW BRUNSWICK	1981	1	90	25	3	0	0
	1982	1	90	27	1	0	0
	1984	1	100	28	13	0	0
	1985	1	80	24	0	0	0
QUEBEC CITY QUEBEC	1980	1	80	24	0	0	0
	1981	1	60	21	0	0	0
	1982	1	110	33	8	1	0
	1983	1	90	34	3	0	0
	1984	1	60	27	0	0	0
	1985	2	130	37	14	5	3
MONTREAL QUEBEC	1976	6	120	37	26	10	4
	1977	7	130	33	23	6	1
	1978	7	120	38	54	24	8
	1979	8	110	31	15	2	1
	1980	8	100	26	5	1	0
	1981	6	120	31	19	5	1
	1882	6	110	32	9	1	0
	1983	7	130	35	18	3	1
	1984	8	90	31	2	0	0
	1985	7	90	28	2	0	0

* AVERAGE OF ALL SITES PER LOCATION

** JUNE TO AUGUST FROM 0900-1600 EST (7 HR. PER DAY)

TABLE 5

SUMMARY OF 7 HOUR SEASONAL MEAN OZONE CONCENTRATIONS FOR SELECTED RURAL AND URBAN LOCATIONS IN SOUTHERN ONTARIO: 1974-1988

LOCATION	URBAN/ RURAL	7 HOUR SEASONAL MEAN* O_3 (ppb) 1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
WINDSOR	U	34	38	56	54	42	39	48	46	40	48	50	44	38	40	62
MERLIN	R	NA	NA	NA	NA	49	NA	43	42	38	42	36	28	33	48	58
LONDON	U	NA	37	43	43	42	36	41	42	40	49	40	40	37	42	53
CENTRALIA	R	NA	NA	NA	48	44	41	38	47	35	48	45	40	41	45	55
SIMCOE	R	54	NA	56	55	55	47	43	52	48	54	52	47	43	49	56
TORONTO a	U	45	60	41	35	39	39	36	40	28	43	38	36	31	36	42
STOUFFVILLE	R	67	61	51	41	54	42	39	29	32	37	35	36	32	41	51
DORSET	R	NA	NA	NA	NA	NA	NA	NA	NA	32	38	38	32	35	40	45
SUDBURY	U	NA	29	NA	23	27	28	19	24	21	19	21	14	23	28	36
OTTAWA	U	NA	39	30	31	NA	29	NA	29	29	33	31	29	27	27	35

a SITE AT DOWNDOWN TORONTO LOCATION (BREADLEBANE)

* JUNE-AUGUST FROM 0900-1600 EST (7 HR PER DAY)

(R) RURAL SITE

(U) URBAN SITE

(NA) NOT AVAILABLE

TABLE 6

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
Dry Bean	1976	Ridgetown, Ont.	Sanilac	CP	NI			26.9				Hofstra et al., 1978
Dry Bean	1976	Talbotville, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1976	Kippen, Ont.	Kentwood	CP	NI				n.s.			
Dry Bean	1976	Elora, Ont.	Seafarer	CP	NI		23.1					
Dry Bean	1977	Stouffville, Ont.	Sanilac	CP	NI		19.3				S.M.=41 wt/1000seeds	Temple and Bisessar, 1979
Dry Bean	1977	Arva, Ont.	Seafarer	CP	NI		20.1					Toivonen et al., 1982
Dry Bean	1977	Ridgetown, Ont.	Seafarer	CP	NI			18.7				
			Sanilac							n.s.		
			Kentwood					20.2				
			Fleetwood					16.4				
Dry Bean	1977	Palmerston, Ont.	Seafarer	CP	NI		18.0					
Dry Bean	1977	Pt. Elgin, Ont.	Seafarer	CP	NI		12.7					

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%)		NON-SIGNIFICANT YIELD LOSS (%)		REMARKS	REFERENCE
							40 ppb	50 ppb	40 ppb	50 ppb		
Dry Bean	1977	Gad's Hill, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1977	Wallacetown, Ont.	Seafarer	CP	NI					n.s.		
Dry Bean	1977	Ripley, Ont.	Sanilac	CP	NI		27.3					
Dry Bean	1977	Elora, Ont.	Sanilac	CP	NI		22.9					
Dry Bean	1977	Belfast, Ont.	Sanilac	CP	NI		21.3					
			Kentwood						n.s.			
Dry Bean	1977	Centralia, Ont.	Sanilac	CP	NI			18.9				
Dry Bean	1977	Varna, Ont.	Sanilac	CP	NI				n.s.			
Dry Bean	1977	Corbett, Ont.	Sanilac	CP	NI					n.s.		
Dry Bean	1977	Kerwood, Ont.	Sanilac	CP	NI				n.s.			
			Sanilac						n.s.			
Dry Bean	1977	Springfield,	Kentwood	CP	NI			22.9				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
		Ont.										
Dry Bean	1977	Benmiller, Ont.	Kentwood	CP	NI		14.2					
Dry Bean	1977	Ingersoll, Ont.	Kentwood	CP	NI				n.s.			
Dry Bean	1978	Wallacetown, Ont.	Seafarer	CP	NI			15.5				Toivonen et al., 1982
Dry Bean	1978	Pt. Elgin, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1978	Arva, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1978	Cromarty, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1978	Tavistock, Ont.	Seafarer	CP	NI			4.5				
Dry Bean	1978	Kippen, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1978	Woodstock, Ont.	Seafarer	CP	NI		3.0					
Dry Bean	1978	Ridgetown, Ont.	Seafarer	CP	NI					n.s.		

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
			Sanilac					21.0				
			Fleetwood							n.s.		
Dry Bean	1978	St. Mary's, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1978	London, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1978	Centralia, Ont.	Seafarer	CP	NI				n.s.			
			Sanilac						n.s.			
			Kentwood						n.s.			
Dry Bean	1978	Gad's Hill, Ont.	Seafarer	CP	NI					n.s.		
Dry Bean	1978	Seaforth, Ont.	Seafarer	CP	NI					n.s.		
Dry Bean	1978	Belfast, Ont.	Sanilac	CP	NI				n.s.			
			Sanilac						n.s.			
Dry Bean	1978	Springfield, Ont.	Sanilac	CP	NI					n.s.		
Dry Bean	1978	Kerwood, Ont.	Sanilac	CP	NI				n.s.			

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
Dry Bean	1978	Ripley, Ont.	Sanilac	CP	NI				n.s.			
Dry Bean	1978	Corbett, Ont.	Sanilac	CP	NI				n.s.			
Dry Bean	1978	Arkell, Ont.	Sanilac	CP	NI				n.s.			
Dry Bean	1978	Benmiller, Ont.	Kentwood	CP	NI				n.s.			
Dry Bean	1978	St. Thomas, Ont.	Kentwood	CP	NI					n.s.		
Dry Bean	1978	Dereham Ctr., Ont.	Kentwood	CP	NI				n.s.			
Dry Bean	1978	Varna, Ont.	Kentwood	CP	NI				n.s.			
Dry Bean	1978	Ingersoll, Ont.	Kentwood	CP	NI				n.s.			
Dry Bean	1978	Nairn, Ont.	Kentwood	CP	NI		3.2					
Dry Bean	1978	Mitchell, Ont.	Seafarer	CP	NI		50.0				S.M.=44	Hucl and Beversdorf,1982
			Sanilac						n.s.			

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
			Kentwood						n.s.			
			Fleetwood						n.s.			
			Ex-Rico 23						n.s.			
			Calima						n.s.			
			Narda						n.s.			
Dry Bean	1978	Elora, Ont.	Seafarer	CP	NI					n.s.		
			Sanilac							n.s.		
			Kentwood							n.s.		
			Fleetwood							n.s.		
			Ex-Rico 23							n.s.		
			Calima							n.s.		
			Narda							n.s.		
Dry Bean	1979	Centralia, Ont.	Seafarer	CP	NI				n.s.		S.M.=41	Hucl and Beversdorf,1982
			Sanilac						n.s.			
			Kentwood						n.s.			

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
			Fleetwood						n.s.			
			Ex-Rico 23						n.s.			
			Calima						n.s.			
			Narda						n.s.			
Dry Bean	1979	Mitchell, Ont.	Seafarer	CP	NI				n.s.		S.M.=41	
			Sanilac						n.s.			
			Kentwood						n.s.			
			Fleetwood						n.s.			
			Ex-Rico 23						n.s.			
			Calima						n.s.			
			Narda						n.s.			
Dry Bean	1979	Ridgetown, Ont.	Seafarer	CP	NI				n.s.		S.M.=39	
			Sanilac						n.s.			
			Kentwood						n.s.			
			Fleetwood						n.s.			
			Ex-Rico 23						n.s.			

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
			Calima						n.s.			
			Narda						n.s.			
Dry Bean	1979	Cromarty, Ont.	Seafarer	CP	NI		7.6					Toivonen,1980
Dry Bean	1979	Wildwood, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1979	Arva, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1979	Belfast, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1979	Elora, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1979	Mitchell, Ont.	Seafarer	CP	NI				n.s.			
			Seafarer						n.s.			
Dry Bean	1979	Hensall, Ont.	Seafarer	CP	NI				n.s.			
			Sanilac						n.s.			
Dry Bean	1979	London, Ont.	Seafarer	CP	NI				n.s.			

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
Dry Bean	1979	Palmerston, Ont.	Seafarer	CP	NI				n.s.			
Dry Bean	1979	Arkell, Ont.	Sanilac	CP	NI				n.s.			
Dry Bean	1979	Kerwood, Ont.	Sanilac	CP	NI				n.s.			
Dry Bean	1979	Benmiller, Ont.	Kentwood	CP	NI				n.s.			
			Fleetwood						n.s.			
Dry Bean	1979	Nairn, Ont.	Kentwood	CP	NI				n.s.			
Dry Bean	1979	Dereham Ctr., Ont.	Kentwood	CP	NI				n.s.			
Dry Bean	1979	Ridgetown, Ont.	Fleetwood	CP	NI				n.s.			
Red Kidney Bean		Ithica, N.Y.	California Light	OTFC-c Aug. 20 - Sept. 10 7hr/d 1000-1700	NI	Y=2878exp[-(O3/.120)*1.171] (Weibull)	11.0	18.1				Kohut and Laurence, 1983
Dry Bean							18.1	18.3				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%)		NON-SIGNIFICANT YIELD LOSS (%)		REMARKS	REFERENCE
							40 ppb	50 ppb	40 ppb	50 ppb		
Potato	1977	Simcoe, Ont.	Norland	CP	I			22.1			S.M.=55	Hofstra et al., 1983
			Superior					17.8				
			Kennebec							n.s.		
Potato	1977	Cambridge, Ont.	Norland	CP	I				n.s.			
			Superior						n.s.			
			Netted Gem						n.s.			
			Kennebec						n.s.			
Potato	1977	Ridgetown, Ont.	Norland	CP	I				n.s.			
			Superior						n.s.			
			Netted Gem				21.1					
Potato	1978	Simcoe, Ont.	Norland	CP	I					n.s.		Hofstra et al., 1983
			Norchip							n.s.		
			Superior					27.8				
			Tobique							n.s.		
			Netted Gem							n.s.		
Potato	1978	Cambridge,	Norland	CP	I				n.s.			

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
		Ont.										
			Norchip						n.s.			
			Superior						n.s.			
			Tobique						n.s.			
			Netted Gem						n.s.			
Potato	1979	Stouffville, Ont.	Norchip	CP	NI		24.2				S.M.=42 with d.c.	Bisessar, 1982
			Norchip				26.2				no d.c.	
Potato	1980-82	Alliston, Ont.	Norchip	CP	NI		17.3		n.s.		no d.c.	Holley et al., 1985
			Chieftan				5.4		n.s.		no d.c.	
			Kennebec				8.1		n.s.		no d.c.	
Potato	1986	State College PA	Norchip	OTFC-p June 25 - Aug. 20 10hr/d 1000-2000	NI	y=11.736-39(O3) (Linear)	5.4	9.1				Pell et al., 1988
Potato							15.4	19.2				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
Onion	1975	Bradford, Ont.	Autumn Spice	CP	I			27.9			S.M.=48	Wukasch and Hofstra, 1977a
			Rocket							n.s.		
Onion	1975	Bradford, Ont.	Autumn Spice	OTFC	I			21.7			S.M.=48	Wukasch and Hofstra, 1977b
Onion	1982	Riverside, Calif.	Evergreen bunching	CTFC Mar. - May 12hr/d 1900-2100	I	Y=11.1-88.1(O3) (Linear)	14.9	24.8				McCool et al., 1987
Onion							14.9	24.8				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
Hay (Alfalfa)	1979	Arkell, Ont.	Algonquin	CP	I				n.s.		S.M.=35	Ensing, 1980
			Anchor						n.s.			
			Angus						n.s.			
			Apollo						n.s.			
			Banner						n.s.			
			Ceres						n.s.			
			Citation						n.s.			
			Iroquois						n.s.			
			Pacer						n.s.			
			Pickstar						n.s.			
			Saranac						n.s.			
			Thor						n.s.			
			Titan						n.s.			
			Valor						n.s.			
			Vernal						n.s.			
			Vista						n.s.			

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
			Weevelchek						n.s.			
			WL-215						n.s.			
			520						n.s.			
(Red clover)			Arlington						n.s.			
			Florex						n.s.			
			Lakeland						n.s.			
			Ottawa						n.s.			
			Prosper I						n.s.			
(Alsike clover)			Merit				21.8					
(White clover)			Ladino-type						n.s.			
(Bird's foot trefoil)			Empire						n.s.			
			Leo				40.8					
			Maitland						n.s.			
			Viking						n.s.			

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
(Red clover)		Cambridge, Ont.	Ottawa	OTFC	I				n.s.			
Hay (Clover/ timothy)	1984	Ithica, N.Y.	Arlington/ Champion	OTFC-p Jun. 28 - Sept. 28 12hr/d, 98d 0800-2000	I	Y=4140.33exp[-(O3/.083)*3.882] (Weibull)	4.8	12.2				Kohut et al., 1988
Hay (Alfalfa)	1984	Shafter, Calif.	WL-514	OTFC-p Mar. 16 - Oct. 10 0900-2000	I	Y=2746-9653(O3)+314 (Linear)	5.1	8.6				Temple et al., 1988
					NI	Y=2746-9653(O3) (Linear)	5.8	9.6				
Hay (Alfalfa)	1984	Bakersfield, Calif.	WL-514	OTFC-p Sept 8 - Oct. 10 0900-2000	I	Y=146.12-216.28(O3)+2.35(pH) (Linear)	2.1	3.5			acid fog at pH 5.6	Temple et al., 1987
Hay (Ladino/ fescue)	1984	Raleigh, N.C.	Regal/ Kentucky 31	OTFC-p Apr. - Oct. 12hr/d 0800-2000	I	Y=1265.98-4480.07(O3) (Linear)	4.0	7.9				Heagle et al., 1988
					NI	Y=1265.98-116.5-4480.07(O3) (Linear)	4.4	8.8				
Hay (Ladino/ fescue)	1985	Raleigh, N.C.	Regal/ Kentucky 31	OTFC-p Apr. - Oct. 12hr/d 0800-2000	I	Y=1057.8-5339(O3) (Linear)	6.0	11.9				Heagle et al., 1989
					NI	Y=1057.8-91.5-5339(O3) (Linear)	6.6	13.2				
Hay	1985	Ithica,	Arlington/	OTFC-p	I	n.s.			n.s.	n.s.		Kohut et al.,

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
(Clover/ timothy)		N.Y.	Champion	Jun. 14 - Oct. 9 12hr/d, 118d 0800-2000								1988
Hay (Alfalfa)	1985	Shafter, Calif.	WL-514	OTFC-p Mar. 23 - Oct. 9 0900-2100	I	Y=1987-41589(O3)*2+1080-6025(O3) (Quadratic)	4.5	7.9				Temple et al., 1988
					NI	Y=1987-41589(O3)*2 (Quadratic)	2.1	4.0				
Hay							9.0	8.8				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
Turnip	1979	Raleigh, N.C.	Tokyo Cross	OTFC-c Oct. 30 - Nov. 28 7hr/d 0920-1620	I	Y=4.05exp[-(O3/.086)*3.0] (Weibull)	7.3	15.8				Heagle et al., 1985
Turnip	1980	Raleigh, N.C.	Tokyo Cross	OTFC-c Oct. 20 - Nov. 26 7hr/d 0900-1600	I	Y=15.25exp[-(O3/.084)*3.94] (Weibull)	2.9	7.5				Heagle et al., 1985
			Just Right			Y=10.89exp[-(O3/.090)*3.05] (Weibull)	6.5	13.6				
			Purple Top White Globe			Y=6.22exp[-(O3/.095)*2.51] (Weibull)	8.3	15.2				
			Shogoin			Y=4.68exp[-(O3/.096)*2.12] (Weibull)	9.5	17.6				
Turnip	1982	Riverside, Calif.	Tokyo Cross	OTFC-c Mar. - May 12hr/d 0900-2100	I	Y=155.5-1026.6(O3) (Linear)	11.9	19.8				McCool et al., 1987
Turnip							7.7	14.9				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
Winter Wheat (soft)	1978	Raleigh, N.C.	Blueboy II	OTFC-c Apr. 9 - May 31	I				n.s.	n.s.	S.M.=60	Heagle et al., 1979c
			Coker 47-27	7hr/d 0930-1630					n.s.	n.s.		
			Holly						n.s.	n.s.		
			Oasis						n.s.	n.s.		
Winter Wheat (soft)	NR	Lafayette Ind.			NI	Y=2077.8(O3)*2-73.8(O3)+.54 (Quadratic)	0.9	2.0				Loehman and Wilkinson, 1983
Winter Wheat (soft)	1982	Argonne, Ill.	Abe	OTFC-c May 8 - Jul. 2 7hr/d, 55d	NI	Y=5235exp[-(O3/.153)*2.272] (Weibull)	3.1	6.1				Kress et al., 1985
			Arthur-71	0900-1600		Y=4513exp[-(O3/.146)*2.58] (Weibull)	2.5	5.2				
			Roland			Y=5426exp[-(O3/.113)*1.734] (Weibull)	8.8	15.6				
Winter Wheat (hard)	1982	Ithica, N.Y.	Vona	OTFC-c May 18 - Jul.22 7hr/d 1000-1500	NI	Y=9103.82exp[-(O3/.04*.853] (Weibull)	28.1	41.7				Kohut et al., 1987
Winter Wheat (hard)	1983	Ithica, N.Y.	Vona	OTFC-c Jun. 12 - Jul. 17 7hr/d 1000-1500	NI	Y=4420.38exp[-(O3/.109*2.735] (Weibull)	7.9	12.8				Kohut et al., 1987
Winter Wheat	1983	Argonne,	Abe	OTFC-c	NI	n.s.			n.s.	n.s.		Kress et al.,

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%)		NON-SIGNIFICANT YIELD LOSS (%)		REMARKS	REFERENCE
							40 ppb	50 ppb	40 ppb	50 ppb		
(soft)		Ill.	Arthur-71	May 8 - Jun. 30 7hr/d, 53d 0900-1600		Y=4910exp[-(O3/.148)*3.781] (Weibull)	0.6	1.6				1985
Winter Wheat							7.4	12.1				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
Soybean	1971	Raleigh, N.C.	Dare	FEC 133d 6hr/d 0800-1400	I					n.s.		Heagle et al., 1974
Soybean	1980	Argonne, Ill.	Corsoy	OTFC-c Aug. 6 - Oct. 9 7hr/d, 56d 0900-1600	NI -	Y=278.5exp[-(O3/.133)*1.952] (Weibull)	5.6	10.4				Kress and Miller, 1983
Soybean	1980	Ithica, N.Y.	Hark	APS-c Aug. 20 - Sept. 12 5.25hr/d, 16d 1030-1545	NI	Y=25.243 - 135.489(O3) (Linear)	9.3	15.5				Reich and Amundson, 1984
Soybean	1981	Ithica, N.Y.	Hodgson	OTFC-c Jul. 23 - Sept. 30 7hr/d, 70d 1000-1700	I	Y=13.32exp[-(O3/.210)*.735] (Weibull)	8.0	13.0				Kohut et al., 1986
Soybean	1981	Raleigh, N.C.	Davis	OTFC-c Jun. 24 - Oct. 12	I	Y=5593exp[-(O3/.128)*.872] (Weibull)	11.5	18.1			Weibull in Heck et al., 1984b	Heagle et al., 1983
Soybean	1981	Beltsville, Md.	Essex	OTFC-c	I	Y=4562exp[-(O3/.187)*1.543] (Weibull)	4.7	8.2			Weibull in Heck et al., 1984b	Heagle et al., 1983
			Williams	OTFC-c	I	Y=4992exp[-(O3/.211)*1.1] (Weibull)	6.3	10.4				
Soybean	1982	Beltsville, Md.	Williams-79	OTFC-c Jul. 23 - Sept. 23	I	Y=5884exp[-(O3/.162)*1.577] (Weibull)	5.6	9.9			Wiebull in Heck et al., 1984b	Heggestad et al., 1985

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
				7hr/d, 63d 0900-1600	NI	Y=4880exp[-03/2.17)*1.0] (Weibull)	6.7	10.9				
			Forrest		I	Y=4333exp[-(03/.171)*2.752] (Weibull)	1.3	2.8				
					NI	Y=5384exp[-(03/.205)*1.0] (Weibull)	7.1	11.5				
Soybean	1982	Raleigh, N.C.	Davis	OTFC-c Jul. 20 - Oct. 17 7hr/d 1000-1700	I	Y=490exp[-(03/.126)*2.17] (Weibull)	5.2	9.9				Heagle et al., 1986
				OTFC-p Jul. 20 - Oct. 17 7hr/d 1000-1700	I	Y=479exp[-(03/.103)*3.89] (Weibull)	2.1	5.5				
Soybean	1982	Lafayette, Ind.	Corsoy		I	Y=619.2(03)-15.5 (Linear)	9.3	15.5				Loehman and Wilkinson, 1983
			Hodgson			Y=414.7(03)-10.4 (Linear)	6.2	10.3				
			Davis			Y=349.9(03)-8.7 (Linear)	5.3	8.8				
			Williams			Y=266.6(03)-6.6 (Linear)	4.1	6.7				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
			Essex			Y=133.4(O3)-3.3 (Linear)	2.0	3.4				
Soybean	1982	New Brunswick, N.J.	Williams	CP Jun. - Sept.	NI				n.s.	n.s.		Smith et al., 1987
			Beeson						n.s.	n.s.		
Soybean	1983	New Brunswick, N.J.	Williams	CP Jun. - Sept.	NI				n.s.	n.s.		Smith et al., 1987
			Cutler 71						n.s.	n.s.		
			Corsoy						n.s.	n.s.		
Soybean	1983	Argonne, Ill.	Corsoy 79	OTFC-c Jul. 28 - Oct. 10	I	Y=1822.5exp[-(O3/.118)*3.082] (Weibull)	2.7	6.1				Kress et al., 1986
			Corsoy 79			Y=2008.5exp[-(O3/.128)*2.467 (Weibull)	3.8	7.7				
Soybean	1983	Beltsville, Md.	Williams-79	OTFC-c Jul. 23 - Sept. 23 7hr/d, 63d	I			13.0			S.M.=52	Heggestad et al., 1988
				0900-1600	NI			13.3				
			Corsoy-79		I					n.s.		

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
					NI			23.5				
Soybean	1983	Raleigh, N.C.	Davis	OTFC-c Jul. 7 - Oct.24 7hr/d 0900-1600	I	Y=473exp[-(O3/.156)*1.89] (Weibull)	2.9	6.4				Heagle et al., 1987b
					NI	n.s.			n.s.	n.s.		
Soybean	1984	Raleigh, N.C.	Davis	OTFC-c Jul. 7 - Oct.18 7hr/d 0900-1600	I	Y=412exp[-(O3/.136)*2.17] (Weibull)	4.4	8.5				Heagle et al., 1987b
					NI	Y=314exp[-(O3/.125)*3.17] (Weibull)	2.1	4.7				
Soybean	1984	New Brunswick, N.J.	Williams	CP Jun. - Sept.	NI				n.s.	n.s.		Smith et al., 1987
			Cutler						n.s.	n.s.		
Soybean							5.3	10.2				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
Spinach	1976	Raleigh, N.C.	America	OTFC-c Sept. 10 - Oct. 17 7hr/d, 38d	I	Y=21.2exp[-(O3/.142)*1.65] (Weibull)	6.5	11.5			Weibull in Heck et al., 1983	Heagle et al., 1979a
			Hybrid 7	0920-1620		Y=36.6exp[-(O3/.139)*2.68] (Weibull)	2.5	5.3				
			Viroflay			Y=41.1exp[-(O3/.129)*1.99] (Weibull)	5.8	10.7				
			Winter Bloomsdale			Y=20.8exp[-(O3/.127)*2.07] (Weibull)	5.0	10.5				
Spinach							5.0	9.5				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
Green Bean	1986	Raleigh, N.C.	BBL-274	OTFC-c Jun. 8 - Jul. 27 7hr/d	I	Y=208exp[-(O3/.127)*4.42] (Weibull)	0.5	1.5				Heck et al., 1988
			Dwarf Hort.	100-1700		Y=124exp[-(O3/.127)*4.42] (Weibull)	0.5	1.5				
			BBL-274	OTFC-c Aug. 6 - Sept. 30 7hr/d		Y=374exp[-(O3/.127)*4.42] (Weibull)	0.6	1.5				
			Dwarf Hort.	1000-1700		Y=205exp[-(O3/.127)*4.42] (Weibull)	0.5	1.5				
			BBL-290	OTFC-c Jun. 8 - Jul. 27 7hr/d		Y=172exp[-(O3/.096)*2.36] (Weibull)	8.2	15.9				
			BBL-254	1000-1700		Y=202exp[-(O3/.096)*2.36] (Weibull)	8.1	15.8				
			BBL-290	OTFC-c Aug. 6 - Sept. 30 7hr/d		Y=362exp[-(O3/.096)*2.36] (Weibull)	8.2	15.9				
			BBL-254	1000-1700		Y=406exp[-(O3/.096)*2.36] (Weibull)	8.1	15.9				
reen Bean							4.3	8.7				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
Flue-cured Tobacco	1983	Raleigh, N.C.	McNair	OTFC-c&p Jun. 2 - Aug. 28 7hr/d 1000-1700	I	Y=322exp[-(O3/.165)*2.12] (Weibull)	3.1	5.9				Heagle et al., 1987a
				OTFC-p Jun. 2 - Aug. 28 12hr/d 1000-2200		Y=335exp[-(O3/.144)*1.71] (Weibull)	6.0	10.7				
Flue-cured Tobacco							4.6	8.3				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
Tomato	1978	Harrow, Ont.	Tiny Tim	CP	NI			23.7				Legassicke and Ormrod, 1981
			New Yorker							n.s.		
Tomato	1980	Harrow, Ont.	H1706	CP	NI				n.s.			Ormrod, 1980
			H2673						n.s.			
			C28						n.s.			
			Veemore						n.s.			
			Veepro						n.s.			
			New Yorker						n.s.			
Tomato	1980	Charing Cross, Ont.	H1706	CP	NI				n.s.			
			H2673						n.s.			
			C28						n.s.			
			Veemore						n.s.			
			Veepro						n.s.			
			New Yorker						n.s.			
Tomato	1980	Simcoe, Ont.	H1706	CP	NI				n.s.		S.M.=43	
			H2673						n.s.			

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
			C28						n.s.			
			Veemore						n.s.			
			Veepro						n.s.			
			New Yorker						n.s.			
Tomato	1980	Cambridge, Ont.	H1706	CP	I				n.s.			Ormrod, 1980
			H2673						n.s.			
			C28						n.s.			
			Veemore						n.s.			
			Veepro						n.s.			
			New Yorker						n.s.			
Tomato	1980	Beltsville, Md.	Jet Star	OTFC Jul. 1 - Sept. 30 7hr/d 1100-1800	I			16.3			S.M.=56	Heggestad et al., 1986
Tomato	1981	Harrow, Ont.	Springset VF	CP	I					n.s.		Ormrod, 1981
			H1350 VF							n.s.		
			C19 VF							n.s.		

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
			Crimson Vee							n.s.		
			Star Shot							n.s.		
			Early Detroit							n.s.		
			H1706							n.s.		
			H2653							n.s.		
			C28							n.s.		
			Veemore							n.s.		
			Tiny Tim							n.s.		
			New Yorker							n.s.		
Tomato	1981	Simcoe, Ont.	Springset VF	CP	I					n.s.	S.M.=52	
			H1350 VF							n.s.		
			C19 VF							n.s.		
			Crimson Vee							n.s.		
			Star Shot							n.s.		
			Early Detroit							n.s.		

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE
			H1706							n.s.		
			H2653							n.s.		
			C28							n.s.		
			Veemore							n.s.		
			Tiny Tim							n.s.		
			New Yorker							n.s.		
Tomato	1981	Tracy, Calif.	Murrieta	OTFC-c 12hr/d 0800-1500	I	Y=32.9exp[-(O3/.142)*3.807] (Weibull)	0.7	1.7				Surano et al., 1987
Tomato	1982	Tracy, Calif.	Murrieta	OTFC-c 12hr/d 0800-1500	I	Y=32.3exp[-(O3/.082)*3.050] (Weibull)	8.2	17.7				Surano et al., 1987
Tomato	1986	Riverside, Calif.	UC-82	OTFC Apr. 15 - Jun. 22 12hr/d 0800-2000	I				n.s.	n.s.		Takemoto et al., 1988
			UC-82	AES	I				n.s.	n.s.		
Tomato							4.5	14.9				

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	50 ppb	REMARKS	REFERENCE
Sweet Corn	1970	Raleigh, N.C.	Golden Midget	OTFC 6hr/d	I					n.s.		Heagle et al., 1972
			White Midget	0800-1400						n.s.		
Sweet Corn	1974	Riverside, Calif.	Bonanza	FEC	I	Y=315.02-(829.9x03) (Linear)	4.2	7.2			Linear in Olszyk et al., 1988a	Thompson et al., 1976
			Monarch Advance				4.2	7.2				
Sweet Corn							4.2	7.2				

Abbreviations:

EXPOSURE PARAMETERS: OTFC = OPEN TOP FIELD CHAMBER
OTFC-c = OTFC WITH CONSTANT O3 ADDITION
OTFC-p - OTFC WITH PROPORTIONAL O3 ADDITION
CTFC = CLOSED TOP FIELD CHAMBER
AES = AIR EXCLUSION SYSTEM
FEC = FIELD EXPOSURE CHAMBER
APS-c = AIR PLENUM SYSTEM WITH CONSTANT O3 ADDITION

SOIL WATER STATUS: NI = NOT IRRIGATED
I = IRRIGATED

EXPT. YIELD MODEL (WEIBULL/OTHER): Y = YIELD
exp = EXPONENTIAL
* = POWER FACTOR

MODELLED OR ACTUAL: MODELLED YIELD LOSS (%) CALCULATED USING CONTROL O3 SEASONAL MEAN AT 0.25 OR .03 ppb (COMPARED TO O3 AT 40 AND 50 ppb)

SUMMARY OF OZONE CROP LOSS LITERATURE WITH YIELD EQUATIONS SOLVED FOR SEASONAL MEANS OF 40 AND 50 PPB

CROP	YEAR	LOCATION	VARIETY	EXPOSURE PARAMETERS	SOIL WATER	EXPT. YIELD MODEL WEIBULL/OTHER	MODELLED OR ACTUAL YIELD LOSS (%) 40 ppb	MODELLED OR ACTUAL YIELD LOSS (%) 50 ppb	NON-SIGNIFICANT YIELD LOSS (%) 40 ppb	NON-SIGNIFICANT YIELD LOSS (%) 50 ppb	REMARKS	REFERENCE

YIELD LOSS (%) — ACTUAL YIELD LOSS REPORTED FOR SEASONAL MEANS OF 40 AND 50 ppb

NON-SIGNIFICANT YIELD LOSS — n.s. = NOT STATISTICALLY SIGNIFICANT AT P=0.05

REMARKS: S.M. = SEASONAL MEAN
d.c. = disease control

REV. MAY 30, 1989

TABLE 7

ADJUSTMENT FACTOR CALCULATION FOR OZONE SENSITIVE CROPS IN ONTARIO

CROP	ADJUSTMENT FACTOR CALCULATION																ADJUSTMENT FACTOR	UNADJUSTED YIELD LOSS		ADJUSTED YIELD LOSS	
	GEOGRAPHIC VARIABILITY				AGRONOMIC VARIABILITY					VALID DATA		EXPERIMENTAL VARIABILITY									
	LOCATION				CULTIVARS		MOISTURE					SIGNIFICANT DATA			MODELLED DATA						
	R-1	R-2	R-3	SUB-FACT (100)	NO.	SUB-FACT (100)	I	NI	SUB-FACT (100)	NO.	SUB-FACT (300)	NO.	%	SUB-FACT (300)	NO.	SUB-FACT (100)		REG. 4 %	REG. 5 %	REG. %	REG.5 %
TOMATO	49		10	85	16	80	51	8	14	59	148	6	10	31	4	7	0.36	4.4	14.9	1.6	5.4
SPINACH		8		50	4	20	8		1	8	20	8	100	300	8	100	0.49	5.0	9.5	2.5	4.7
SOYBEAN	18	47		64	10	50	37	28	44	65	163	47	72	217	46	71	0.61	5.3	10.2	3.2	6.2
GREEN BEAN		16		50	4	20	16		1	16	40	16	100	300	16	100	0.51	4.3	8.7	2.2	4.4
ONION	3		2	64	3	15	5		1	5	13	4	80	240	2	40	0.37	14.9	24.8	5.6	9.2
POTATO	30			100	7	35	20	10	34	30	75	11	37	110	2	7	0.36	15.4	19.2	5.6	6.9
S. CORN		2	4	23	4	20	6		1	6	15	4	67	200	4	67	0.33	4.2	7.2	1.4	2.3
TURNIP		10	2	43	5	25	12		1	12	30	12	100	300	12	100	0.50	7.7	14.9	3.8	7.4
F. C. TOBACCO		4		50	1	5	4		1	4	10	4	100	300	4	100	0.47	4.6	8.3	2.1	3.9
W. WHEAT	4	20		58	8	40	8	16	67	24	60	14	58	175	14	58	0.46	7.4	12.1	3.4	5.5
DRY BEAN	112			100	8	40		112	100	112	280	24	21	64	2	2	0.59	18.1	18.3	10.6	10.7
HAY	35	8	10	75	20	100	45	8	16	53	133	22	42	125	20	38	0.49	9.0	8.8	4.4	4.3

GEOGRAPHIC VARIABILITY - LOCATION

R-1 = REGION 1 [ONT. AND NE STATES] (eg. N.J., N.Y., PA., CONN., MICH., OHIO, VT., N.H., MASS., MA., R.I.)

R-2 = REGION 2 [SE, MID-W AND W STATES] (eg. MD., NC., SC., W.V., V, WISC., ILL., IND., IOWA, MINN., OR., WASH.)

R-3 = REGION 3 [SW STATES] (eg. CALIF.)

AGRONOMIC VARIABILITY - MOISTURE

I = IRRIGATED

NI = NOT IRRIGATED

ADJUSTMENT FACTOR = [SUM(ALL SUB-FACTORS)]/1000

TABLE 8

SUMMARY OF ESTIMATED CROP LOSS DUE TO OZONE EXPOSURE IN ONTARIO

CROP	AVERAGE YIELD LOSS IN ONTARIO - OZONE REGION 4	OZONE REGION 5
AT RISK		
Dry Beans	10.6	10.7
Potato	5.6	6.9
Onion	5.6	9.2
Hay	4.4	4.3
Turnip/Rutabagas	3.8	7.4
Winter Wheat	3.4	5.5
Soybean	3.2	6.2
Spinach	2.5	4.7
Green/Snap Bean	2.2	4.4
Flue-cured Tobac	2.1	3.9
Tomato	1.6	5.4
Sweet Corn	1.4	2.3
MARGINALLY AT RISK		
Cucumber	1	2
Squash	1	2
Pumpkin	1	2
Melon	1	2
Grapes	1	2
Burley Tobacco	1	2
Beet	1	2
POTENTIALLY AT RISK		
Radish	0	0
Pea	0	0
Carrot	0	0
Celery	0	0
Cabbage	0	0
Cauliflower	0	0
Eggplant	0	0
Pepper	0	0
Sunflower	0	0
Peanut	0	0
Field Corn	0	0
Strawberry	0	0
Spring Barley	0	0
Apple	0	0
Oats	0	0

TABLE 9 Summary of Phytotoxicology Foliar Injury Assessments in Southern and Central Ontario 1971 - 1986

Crops Examined	No. Years Assessed	Total No. Visual Assessments
White bean	16	690
Tomato	13	907
Potato	10	557
Flue-cured tobacco	3	51
Sweet corn	2	40
Green onion	3	26
Snap bean	2	23
Cucumber	3	22
Celery	3	19
Radish	3	15
Grapes	1	15
Burley tobacco	2	14
Carrot	3	13
Beets	3	11
Set onion	2	11
Green bean	1	11
Pea	1	11
Romaine lettuce	2	10
Spanish onion	2	10
Cooking onion	2	9
Head lettuce	1	9
Soybean	2	8
Spinach	2	7
Leaf lettuce	3	7
Eggplant	1	5
Zucchini	1	5
Oats	1	4
Peanut	1	4
Boston lettuce	1	3
Peppers	1	3
Squash	1	3
Swiss chard	2	2
Field corn	1	2
Barley	1	2
Yellow bean	1	2
Broccoli	1	1
Cabbage	1	1
Endive	1	1
Leek	1	1
Watermelon	1	1
TOTAL 40	102	2536

TABLE 10

CALCULATED CROP PRODUCTION INCREASES DUE TO OZONE REDUCTION: REG 4

Crop Average Price (1985-1987) ($/tonne)	Potential Area of O3 Exposure	Average Ann. Production Pc 1985-1987 (tonnes)	Production Increase Factor (%L/100%-%L)	Potential Production Increase P (tonnes)	$ Value of Production Increase ($)
BEET $457.10	Min.	4379	0.0101	44.2	20219
	Mean	6826	0.0101	68.9	31517
	Max.	1409	0.0101	14.2	6506
CUCUMBER $411.88	Min.	2755	0.0101	27.8	11462
	Mean	3630	0.0101	36.7	15102
	Max.	814	0.0101	8.2	3387
GRAPES $431.90	Min.	11605	0.0101	117.2	50628
	Mean	69577	0.0101	702.8	303538
	Max.	1247	0.0101	12.6	5440
MELON $628.49	Min.	366	0.0101	3.7	2324
	Mean	732	0.0101	7.4	4647
	Max.	1098	0.0101	11.1	6971
PUMPKIN & SQUASH $40.39	Min.	3496	0.0101	35.3	1426
	Mean	6992	0.0101	70.6	2853
	Max.	10488	0.0101	105.9	4279
BURLEY TOBACCO $2979.92	Min.	45	0.0101	0.5	1355
	Mean	91	0.0101	0.9	2739
	Max.	136	0.0101	1.4	4094
GREEN/SNAP BEANS $732.23	Min.	3195	0.0225	71.9	52626
	Mean	4406	0.0225	99.1	72573
	Max.	1171	0.0225	26.3	19288
SWEET CORN $464.33	Min.	8060	0.0142	114.4	53139
	Mean	21225	0.0142	301.4	139935
	Max.	35871	0.0142	509.3	236495
ONIONS $512.00	Min.	10791	0.0593	640.1	327754
	Mean	76483	0.0593	4537.1	2323009
	Max.	35772	0.0593	2122.1	1086499
POTATOES $154.00	Min.	48480	0.0593	2875.9	442894
	Mean	255586	0.0593	15161.9	2334930
	Max.	192936	0.0593	11445.4	1762585
TURNIP/RUTABAGAS $131.33	Min.	21442	0.0395	847.0	111234
	Mean	36734	0.0395	1451.0	190564
	Max.	6648	0.0395	262.6	34488
SPINACH $599.00	Min.	896	0.0256	23.0	13762
	Mean	1472	0.0256	37.7	22608
	Max.	632	0.0256	16.2	9707
TOMATOES $499.33	Min.	14834	0.0163	241.2	120440
	Mean	41908	0.0163	681.4	340259
	Max.	11348	0.0163	184.5	92137
WINTER WHEAT $133.33	Min.	348730	0.0104	3610.0	481327
	Mean	712810	0.0104	7379.0	983840
	Max.	205300	0.0104	2125.3	283361
HAY (Legumes) $59.30	Min.	940453	0.0460	43284.4	2566768
	Mean	4235740	0.0460	194950.4	11560557
	Max.	5062290	0.0460	232992.4	13816451
SOYBEANS $245.67	Min.	497810	0.0331	16456.5	4042875
	Mean	935540	0.0331	30926.9	7597822
	Max.	68350	0.0331	2259.5	555092
DRY BEANS $460.33	Min.	36225	0.1186	4295.1	1977179
	Mean	64100	0.1186	7600.2	3498611
	Max.	9780	0.1186	1159.6	533797
FLUE-CURED TOBACCO $3814.67	Min.	50915	0.0215	1092.2	4166192
	Mean	32314	0.0215	693.2	2644139
	Max.	946	0.0215	20.3	77408

TABLE 11

CALCULATED CROP PRODUCTION INCREASES DUE TO OZONE REDUCTION: REG 5

Crop Average Price (1985-1987) ($/tonne)	Potential Area of O3 Exposure	Average Ann. Production Pc 1985-1987 (tonnes)	Production Increase Factor (%L/100%-%L)	Potential Production Increase P (tonnes)	Value of Production Increase ($)
BEET	Min.	----			
$457.10	Mean	813	0.0204	16.6	7584
	Max.	6782	0.0204	138.4	63266
CUCUMBER	Min.	----			
$411.88	Mean	1256	0.0204	25.6	10558
	Max.	4389	0.0204	89.6	36893
GRAPES	Min.	----			
$431.90	Mean	0	0.0204	0.0	0
	Max.	68372	0.0204	1395.3	602650
MELON	Min.	----			
$628.49	Mean	146	0.0204	3.0	1873
	Max.	293	0.0204	6.0	3758
PUMPKIN & SQUASH	Min.	----			
$40.39	Mean	1398	0.0204	28.5	1152
	Max.	4938	0.0204	100.8	4070
BURLEY TOBACCO	Min.	----			
$2979.92	Mean	18	0.0204	0.4	1095
	Max.	36	0.0204	0.7	2189
GREEN/SNAP BEANS	Min.	----			
$732.23	Mean	617	0.0460	28.4	20793
	Max.	4404	0.0460	202.7	148419
SWEET CORN	Min.	----			
$464.33	Mean	3109	0.0235	73.2	33984
	Max.	16693	0.0235	393.0	182471
ONIONS	Min.	----			
$512.00	Mean	0	0.1013	0.0	0
	Max.	44251	0.1013	4483.6	2295594
POTATOES	Min.	----			
$154.00	Mean	8292	0.0741	614.6	94641
	Max.	97783	0.0741	7247.1	1116050
TURNIP/RUTABAGAS	Min.	----			
$131.33	Mean	163	0.0799	13.0	1711
	Max.	31703	0.0799	2533.5	332725
SPINACH	Min.	----			
$599.00	Mean	153	0.0493	7.5	4520
	Max.	1147	0.0493	56.6	33884
TOMATOES	Min.	----			
$499.33	Mean	7201	0.0571	411.1	205250
	Max.	38800	0.0571	2214.8	1105916
WINTER WHEAT	Min.	----			
$133.33	Mean	48360	0.0582	2814.6	375271
	Max.	586870	0.0582	34156.5	4554080
HAY (Legumes)	Min.	----			
$59.30	Mean	189750	0.0449	8525.9	505584
	Max.	1708550	0.0449	76768.7	4552384
SOYBEANS	Min.	----			
$245.67	Mean	59700	0.0661	3946.1	969427
	Max.	952290	0.0661	62944.5	15463586
DRY BEANS	Min.	----			
$460.33	Mean	350	0.1198	41.9	19305
	Max.	55050	0.1198	6596.1	3036400
FLUE-CURED TOBACCO	Min.	----			
$3814.67	Mean	29199	0.0406	1185.0	4520289
	Max.	60574	0.0406	2458.3	9377443

TABLE 12

TOTAL CALCULATED PRODUCTION INCREASES DUE TO OZONE REDUCTIONS: TOTAL FOR REGIONS 4 & 5

CROP AVERAGE PRICE 1985 - 1987 ($/tonne)	POTENTIAL AREA OF EXPOSURE		
	MINIMUM ($)	MEAN ($)	MAXIMUM ($)
BEET $457.1	20,219	39,101	69,772
CUCUMBER $411.88	11,462	25,660	40,279
GRAPES $431.90	50,628	303,538	608,091
MELON $628.49	2,324	6,520	10,729
PUMPKIN & SQUASH $40.39	1,426	4,005	8,349
BURLEY TOBACCO $2979.92	1,355	3,834	6,283
GREEN/SNAP BEANS $732.23	52,626	93,367	167,707
SWEET CORN $464.33	53,139	173,919	418,966
ONIONS $512.00	327,754	2,323,009	3,382,092
POTATOES $154.00	442,894	2,429,571	2,878,634
TURNIP/RUTABAGAS $131.33	111,234	192,275	367,212
SPINACH $599.00	13,762	27,128	43,591
TOMATOES $499.33	120,440	545,509	1,198,052
WINTER WHEAT $133.33	481,327	1,359,111	4,837,441
HAY (Legumes) $59.30	2,566,768	12,066,141	18,368,835
SOYBEANS $245.67	4,042,875	8,567,249	16,018,678
DRY BEANS $460.33	1,977,179	3,517,916	3,570,197
FLUE-CURED TOB $3814.67	4,166,192	7,164,428	9,454,851
TOTAL	14,443,603	38,842,280	61,449,760

TABLE 13

TOTAL PRODUCTION INCREASES FOR ORNAMENTAL CROPS FROM OZONE CONTROL

SECTOR	TOTAL PRODUCTION $	POTENTIAL PRODUCTION INCREASE $ MINIMUM (2%)*	MEAN (5%)**	MAXIMUM (7%)***
CHRISTMAS TREES	9500000	193800	499700	715350
PROVINCIAL NURSERIES	854300	17428	44936	64329
PRIVATE NURSERIES				
TREES	66342825	1353394	3489633	4995615
SOD	32176969	656410	1692509	2422926
TOTAL	108874094	2221032	5726777	8198219

* to convert 2% loss to production increase multiply by 0.0204
** to convert 5% loss to production increase multiply by 0.0526
*** to convert 7% loss to production increase multiply by 0.0753

TABLE 14

VALUE OF PRODUCTION INCREASES FOR AGRICULTURAL AND ORNAMENTAL CROPS FROM OZONE CONTROL

VEGETATION TYPE	POTENTIAL MINIMUM	PRODUCTION MEAN ($ IN MILLIONS)	INCREASE MAXIMUM
AGRICULTURAL CROPS	14.4	38.8	61.4
ORNAMENTALS	2.2	5.7	8.2
TOTAL	16.6	44.5	69.6